TRENDS IN JAPANESE TEXTILE TECHNOLOGY

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Foreword

The U.S. Department of Commerce's Office of Technology Policy (OTP) is pleased to release a new report in our series on the global economy and competitiveness assessment. *Trends in Japanese Textile Technology* highlights the advances that have propelled Japan to the forefront of apparel textile innovation.

Since 1987, OTP's Asia-Pacific Technology Program has helped U.S. companies and researchers leverage foreign science and technology through the publication of high-quality technical assessments and studies and many other activities. This report continues our tradition of providing U.S. organizations with the specialized information they need to make educated business decisions on technology-related questions.

Trends in Japanese Textile Technology shows that the emergence of a world-class textile technology in Japan resulted from close cooperation among all segments of the industry, including producers of fibers and yarns, fabrics, apparel, and processing equipment. All the producers are driven by a relentless attention to product quality. Japan is working hard to maintain its technical leadership by increasing the pace of process innovation and expanding longer-range fundamental research in both materials and manufacturing.

The report discusses the current upheaval in the industry caused by import competition and the subsequent need for downsizing. The Japanese textile industry is coping with these trends by paying increased attention to innovative manufacturing practices. And finally, it is adopting new business strategies that reflect an increased premium on technology, marketing, and management expertise.

We sincerely hope you find the information in this report interesting and beneficial. As always, listening to industry is part of our primary mission. Your comments are most welcome.

Graham R. Mitchell
Assistant Secretary of Commerce for Technology Policy

About the Author

Dr. Berkowitch retired from Dupont Fibers, Technical Division, following a thirty-four-year career in various staff and managerial positions and is currently an independent consultant on Japanese textile technology to U.S. industry, the National Textile Center—a university research consortium funded by the U.S. Department of Commerce, and the U.S. Department of Energy. He also served on the faculty of the Philadelphia College of Textiles and Science Graduate Program.

Executive Summary: Trends in Japanese Textile Technology

This report describes the strategies and technologies that have propelled Japan to the forefront of apparel textile innovation. Practically every facet of the industry is covered—from technological advances in fiber and yarn manufacturing, fabric making, apparel design and production, and the development of related equipment to the economics of offshore production and the role of government. But most importantly, the textile industry's long history of striving for upgraded quality in product and process technology, and more recently, its accelerating globalization to counter the threat of imports into its domestic market, provide insight into how Japan likely will face the challenges of a strong yen, a maturing economy, and structural change and deregulation of its industries in the coming years.

These developments are described in detail in this three-part report *Trends in Japanese Textile Technology*. Part One provides an overview of the current business environment. Part Two surveys Japan's state-of-the-art textile technology in characterization, products, and manufacturing. Part Three discusses the likely directions research and development will take to cope with an increasingly cost-conscious consumer market, increased import competition, and the movement offshore of a significant portion of Japan's manufacturing base.

Throughout the report it is demonstrated that the emergence of a world-class textile technology in Japan results from close cooperation among all segments of the industry and relentless attention to end-product quality. The many technology achievements are based upon deep insights gained over time of how quality could be improved across products and processes and costs could be reduced. To fully appreciate these technologies and methodologies, the report addresses the progress in characterization and surveys the broad range of products that have come on the scene during the last two decades. The focus is on specialties, rather than commodities, due to their leading-edge technologies. The flexibility and sophistication of the industry's manufacturing capability is examined in light of the rapid scale-up of complex fiber production and fabric finishing procedures. The review concludes with advances in the making of fibers and yarns, fabrics, and apparel, demonstrating the role of productivity and automation, and the need for skilled domestic textile equipment manufacturing capability.

The following technical advances stand out because of the scope of their contributions to maintaining industry competitiveness:

1. The creation of a methodology that permits producers to objectively specify qualities of fabrics and apparel (e.g., hand, tailorability, drape).

2. The rise of a wide range of specialty fabrics, especially ultrafine filament yarns, that ushered in a new age for synthetics by conferring new dimensions to tactile and visual aesthetics.

3. The optimization of chemical and mechanical fabric finishing in maximizing yarn potential, which in turn has been key to creating successful products.

4. The steady increase in processing speed and automation throughout the production chain.

5. The demonstrated feasibility of completely automating the manufacture of tailored garments through the application of robotics to flexible materials.

The report concludes noting that:

- The future research and development agenda will place a priority on manufacturing innovation to increase worldwide competitiveness.

- This agenda also will shift from applied to basic research in materials and manufacturing. Two new areas of basic research involve shape-memory polymers (smart fabrics) and the design of products guided by the physiological responses of the end users (kansei engineering).

It is hoped that these insights into Japanese textile strategies and technology developments will assist American industry. Japan's offshore production and technological innovations will most certainly mean greater challenge to U.S. companies in their own and third-country markets. Regardless of one's interest in textiles though, this report will contribute to understanding the dynamics that will help drive Japanese industry into the next century.

Introduction

Textiles enjoy a special status in Japanese society, because of tradition, affluence, and overcrowding. Dress, rather than living quarters or the automobile, is of paramount importance in projecting an individual's image. Living quarters are exiguous and the automobile is made unwieldy by the traffic density and the competition from efficient public transportation. This social importance may well have helped drive steady quality improvements and the proliferation of premium products during the past three decades. A strong technical infrastructure, manufacturing base, equipment production capability, and consumer demand have permitted the industry not only to meet domestic needs but also to move to the forefront of apparel textile innovation.

Achieving this premier status was part of a comprehensive business strategy that included a broad penetration of global markets via exports. However, successive revaluations of the yen against the currencies of industrialized nations have shaken Japan's position. The country is trying to overcome the hurdle and make its offerings more competitive globally by moving manufacturing facilities offshore, primarily to low-labor-cost Asian countries. Thus, the Japanese textile industry, via its foreign subsidiaries, will soon again challenge its U.S. and European counterparts. Because of this impending threat, it is appropriate to survey the technologies that placed Japan at the leading edge of the art.

The first part of this report gives an overview of the business environment and a perspective on the potential impact these offshore moves may have on the future, particularly of the U.S. textile market. Emphasis is placed on the trade balance, the globalization profile, and the core strategy.

The second part of the report highlights the state of the art, with advances in characterization, product, and manufacturing representing the industry's high quality standards today.

Observations are interspersed to help the reader understand the thinking and methodologies that have guided the steady ascent of Japanese textile technology.

The report's third part attempts to predict the focus of research in the years ahead and how that focus might be affected by an increasingly cost-conscious domestic consumer and overseas manufacturing operations.

The report presents facts and comments that emerged from regular contacts with industry, academia, and government personnel; from participation in technical events; and from a review of the literature. Bibliographic references are appended to each part.

The report's focus is apparel textiles. Hence, only passing references are made to trends in semitextile and industrial fiber products.

ACRONYMS

ASEAN	Association of South East Asian Nations: Brunei, Indonesia, Malaysia, Philippines, Singapore, and Thailand
CSIRO	Commonwealth Scientific and Industrial Research Organization
EU	European Union (formerly European Economic Community)
FAST	Fabric Assurance by Simple Testing
GATT	General Agreement on Tariffs and Trade
KES	Kawabata Evaluation System
MFA	Multi-Fiber Arrangement
MITI	Ministry of International Trade and Industry (Japan)
NAFTA	North American Free Trade Agreement
NIE	Newly Independent Economies: Hong Kong, Korea, and Taiwan
TRAASS	Technology Research Association of Automated Sewing System
WTO	World Trade Organization

PART 1

Business Environment

The sharp appreciation of the yen, the growth of manufacturing bases in Asia, and the formation of regional economic blocs in North America and Europe have dramatically affected all levels of the textile industry. A review of government statistics and trade press at the time of this writing conveys the magnitude of the upheaval.[1–4]

1.1. Trade Balance

During 1982–1994, Japan's imports of fibers, textiles, and fabricated products grew from $3.1 billion to $22.2 billion to meet more than half of the domestic demand. The trend is expected to accelerate, with import penetration reaching 70 percent by the turn of the century. Apparel imports alone amounted to $15 billion in 1995, with China contributing about 53 percent of the total and as much as 80 percent in specific market segments, such as knitted sweaters. During the same 12-year period, exports increased from $5.6 billion to just $8.4 billion. Hence, the trade balance passed from +$2.5 billion to –$13.8 billion, an all-time record. The balance turned negative in 1987, and in a matter of very few years, the once-flourishing industry was literally struggling. Doubtful about the success of MITI's interventions under the MFA and the outcome of antidumping court actions, the industry adopted the alternate course of globalization.

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1.2. Globalization

Japan's manufacturing base is gradually moving offshore to China, the ASEAN countries, and—to a lesser degree—Europe. In 1988, 106 Japanese enterprises invested $149 million in Asian countries. By 1992, these investments had nearly doubled, with 252 Japanese enterprises investing $227 million in Asian countries (81 percent of Japanese firms and 53 percent of Japanese investments offshore).

1.2.1. Expansion into South and East Asia

China by far received the largest share of these investments, seeing new Japanese-financed facilities go annually from 23 to 187, and capital expenditures from $16 million to $120 million. Since 1992, the pace has quickened.

Japanese apparel manufacturers were the first to shift offshore about a decade ago to tap the large pool of low-cost labor. They stood to gain the most because their operations were the most labor intensive in the industry complex and required the least investment. Japan exported fabrics and imported finished garments. However, an explosion of imports of all kinds ensued, leaving weavers with little choice but to similarly locate facilities abroad. The gradual hollowing-out of the industry that is under way has led finishers and fiber producers to now envision the same. Some fiber producers have decided to establish fully integrated manufacturing bases abroad that will supply yarns, fabrics, and apparel not only to Japan, but also to China and the rest of the world. In addition, Vietnam and India have entered the Japanese investment orbit, in part because of the pressure created by the growing presence of NIE competitors who are faced with raising labor costs at home.

As a result of these moves, South and East Asia already produce 46 percent of the world's synthetic fibers and 42 percent of its cotton yarns. At the same time, they export 38 percent of the textile goods and 43 percent of the apparel, with Japan being the closest and most attractive major market.

1.2.2. Impact on Japan

The yen's appreciation launched a recession and subsequent price war that has undermined Japan's heavy and complex distribution system. The more conscious consumers are welcoming the large-volume outlets, which for the past two to three years have challenged department stores and small shops alike to meet their bargain prices. These mass merchandisers play it two ways. On the one hand, they encourage apparel manufacturers to produce overseas, and on the other, they establish ties with Japanese trading houses sourcing overseas. Of forty-one manufacturers, only seven currently do not handle foreign goods. The thirty-four others have anywhere from 3 to 60 percent of their in-house brands made overseas. The financial situation of their Japanese subcontractors is consequently getting weaker. An aging workforce and the labor shortage do not help. In summary, supply lines are being shortcut, leaving out the middleman.

The largest apparel manufacturers have responded by producing quick-delivery volume items overseas and high-value specialties in Japan, where they rely on subcontractors to lower costs. Many do not expect this approach to be successful for long. They fear direct ties between the volume outlets at home and the fully integrated manufacturing bases of

Japanese fiber producers that are emerging abroad (Part 1, Sec. 1.2.3), which would reduce Japanese apparel manufacturers to the role of plain contractors, despite their own overseas operations.

1.2.3. Role of the Fiber Producer

In this process of globalization, fiber producers occupy a unique position that has growing business and technological relevance to the U.S. textile industry. The establishment of these fully integrated manufacturing bases abroad will indeed enable Japanese firms to control the entire fabrication process and bring to bear the know-how that made them the leaders in textile innovation.

Two recent developments involving a major fiber producer are symptomatic of this trend. Using its factories in Malaysia, this fiber producer makes the fabric for one out of every five dress shirts sold in the United States. No stage of fabrication is handled in Japan.[5] This same producer has revamped mills in the United Kingdom that it acquired from a large British textile concern and built a new plant as well, making it now the largest European producer of polyester woven fabrics to operate a state-of-the-art integrated weaving and dyeing facility.[6] Besides these installations in Malaysia and the United Kingdom, it has seventeen sites scattered across Indonesia, Thailand, Hong Kong, and Italy that produce various synthetic fiber yarns and knitted and woven fabrics. All told, its polyester capacity in South and East Asia has reached 75 percent of its domestic level. It has also announced a plan for an integrated polyester business in China that will extend from fiber spinning to fabric finishing. Meanwhile, it has begun importing into Japan a comprehensive array of products, including fibers, yarns, gray and dyed fabrics, and garments manufactured at its overseas sites. The initiative is designed not to compete with its own Japanese customers, but to defend its share of specific markets that are threatened by imports.

All of the eight largest fiber producers have overseas operations, albeit not as encompassing as those just mentioned. Most have had a presence in South and East Asia for some time, and lately have moved into China or are poised to do so. Many also have joint manufacturing ventures in Europe. One of them has announced its intention to manufacture in the United States.[7]

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1.3. Strategy

The textile industry's rise on the world scene is the result of a broad and thorough plan implemented with unwavering determination. Even in

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today's fast-evolving environment, its objectives have not changed, although some of its means have. The plan has guided the growth of the entire Japanese industrial establishment. It has the following characteristics:

- Comprehensive. The plan addresses manufacturing, product, and equipment development needs equally. Early on, the focus was on lowering cost and improving the quality of commodities for domestic consumption and export. But with growing prosperity at home, the focus expanded to include value-added specialties and flexible routes for their production, which, in time, became one of the hallmarks of the industry. A strong systemic perspective prevails throughout the industry because of close collaboration among all segments from fiber producers to fashion designers, including the small and medium enterprises that employ three-quarters of the workforce. These enterprises are meaningful partners because of the support they receive from a network of centers funded by the national, prefectural, and municipal governments.[8,9] Operating on a regional level with a professional staff of hundreds, the centers inform, train, guide, fund research and development (R&D), and offer the use of experimental facilities to small companies.

- Global. The plan aims to tailor products to the regional preferences of any population. The pace at which manufacturing operations are moving offshore facilitates that goal by providing the ability to adjust to circumstances. Equally important is the scope of intelligence and technology transfer activities conducted worldwide by both industry and government. Personnel stationed abroad periodically brief corporate management in Japan on their findings. Considerable attention is given to postgraduate and professional education overseas. For example, for every one American studying in Japan, there are twenty-five Japanese researchers in the United States.[10]

- Long range. The continuity of effort, especially in R&D and capital investment, even during business slowdowns, contrasts with the on-again, off-again practices of Japan's Western competitors. Research funding for all industries in Japan rose steadily from 1978 through 1992.[11,12] In 1993, the last year for which information is available, the lingering recession caused a slight drop in R&D funding (1.4 percent) for the first time, from a record level of $137 billion. Equally revealing is the shift of corporate emphasis from product to basic research. That consistent focus on business fundamentals in a changing environment has produced strings of incremental advances, notably in quality improvements, that have played a major role in the ascent of the industry.

1.4. Implications for Research and Development

The rapidly growing textile trade deficit, the moving offshore of substantial portions of the manufacturing base, and the increasingly cost-conscious consumer market will test the comprehensive character of the industry's three-pronged strategy. In particular, a strong competitive domestic environment and high-priced exports will force a focus on economics with an emphasis on innovation in manufacturing technologies. The closing of facilities and curtailment of personnel will create additional constraints on the capability to conduct a broad range of activities. Therefore, redeployment of technical resources appears unavoidable, but these measures are not expected to threaten Japan's leadership in innovation for the time being.

1.5. Notes

[1] "MITI World Textile Report." Ministry of International Trade and Industry, April 1994.

[2] "Textiles Trade Deficit Renews Record." JTN Weekly **21** [10], March 10, 1995, p. 3.

[3] "Textiles & Apparel Industry in the Asian Age." JTN **482**, January 1995, p. 12.

[4] "New Course of Japanese Textile Industry." JTN **478**, September 1994, p. 22.

[5] "To Stay Competitive, Toray Keeps Changing Its Colors." The Wall Street Journal, December 30, 1994.

[6] "Toray Textiles Europe." Knitting International **100** (1197), September 1993.

[7] "Teijin Commences Feasibility Study on Advancing Business to U.S." JTN **481**, December 1994, p. 21.

[8] "Local Centers Upgrade Technology of Japanese Small Manufacturers." NTIS Alert—Foreign Technology **91** [43], October 22, 1991.

[9] "Kosetsushi and Technology Reinforcement of Small and Medium Companies, February 1994" [see Japanese Technical Literature Bulletin **25**, U.S. Department of Commerce, December 1994].

[10] "Facing Japan as a Technological Superpower." MIT Japan Science and Technology—Newsletter **1** [1], January 1993.

[11] "R&D Spending: State of Japanese Research." Science, November 18, 1994 [see Japanese Technical Literature Bulletin **25**, U.S. Department of Commerce, December 1994].

[12] "R&D Spending: Science and Technology Research in FY 1993." Report from the Prime Minister's Office, Nikkan Kogyo Shimbun, December 1, 1994 [see Japanese Technical Literature Bulletin **25**, U.S. Department of Commerce, December 1994].

PART 2

State of the Art

The Japanese textile industry complex, driven by constant attention to end-product quality, has developed insights into products and manufacturing processes that have led to its current technical leadership. All segments of the complex participated in this endeavor by sharing characterization results, improving procedures and equipment, and introducing novel product and fabrication concepts. Such groundbreaking cooperation, traceable to the 1960s, is a hallmark of the industry. It contrasts with the prevailing situation in the United States and Europe, where technical support, if strong at the fiber-producer end, consistently weakens along the chain to become negligible at the apparel-making level.

This part of the report highlights key advances in characterization, products, and manufacturing.

Characterization

1.1. Objective Specification of Fabric and Apparel Qualities

The characterization accomplishment that most affected the textile business was the development of methods for expressing key subjective qualities of fabrics and garments as functions of mechanical and physical parameters. This accomplishment spawned a rigorous discipline that would help meet many outstanding needs. The relative merits of two products, for instance, could be assessed against objectively measured quantities. This advance would prove valuable to both product development and trade-claim settlements involving product mergers. The generation of quantitative process-product correlations would permit optimization without input from experts, whose numbers on the factory floor are rapidly decreasing. Such quantification would also make it possible to envision the complete automation of tailored garment manufacture, which demanded programming on the basis of product qualities (Part 2, Sec. 3.3.1).

The characterization accomplishment that most affected the textile business was the development of methods for expressing key subjective qualities of fabrics and garments as functions of mechanical and physical parameters.

1.1.1. Tailorability (via Fabric Hand)

The most significant contribution to the field of characterization was prompted by the desire of men's suit manufacturers to improve tailorability, primarily in jacket appearance. Tailorability had been based on visual examination and predicted subjectively via the fabric hand. A substantial effort involving academia and industry produced a two-step method known as the Kawabata Evaluation System (KES), to quantitatively characterize that hand.[1-4] This method is now used across the Japanese textile industry and has helped specify other subjective qualities, such as drape and sewability.

The first step provided the terminology, scales, and experimental approach—for example, how to manipulate fabric samples with the hands to express tactile perceptions quantitatively and reproducibly. Fabric portfolios for each fabric class (winter suiting, summer suiting, dress wear, etc.) became commercially available as references. Each item in the portfolio was tagged with numbers reflecting the experts' perceptions. A side-by-side tactile comparison by a nonexpert then sufficed to estimate, by interpolation, the corresponding numbers for any new fabric. The perceptions varied with fabric class and typically included stiffness, smoothness, fullness, crispness, and an overall hand quality assessment. The trade began to explore the merits of using such numbers to conduct transactions at a distance, thus doing away with the need to manipulate fabric samples.

The second step sought to develop a predictive capability for these tactile perceptions. All fabrics in the reference portfolios were subjected to deformations similar to those applied by the experts' hands, using the same modes and rates and employing four new laboratory instruments. The modes included bending, shearing, tensioning, compressing, and stroking. Regressions carried out on the sixteen KES parameters characterizing the various stress-strain curves produced calculated values for the magnitudes of the tactile perceptions. In many instances, these values agreed well with those of the experts. Thus it became possible to replace tactile perceptions with KES parameters, expressed mostly in cgs (centimeter-gram-second) units, and the reference fabric portfolios became obsolete. An illustration of the ground covered by the industry in that regard can be seen in Japanese press releases concerning new fabrics which today often mention key values of such parameters. Although the KES method has received worldwide validation, some continue to express reservations about selected aspects of the data treatment procedure.

Turning back to their original objective, suit manufacturing experts subsequently correlated tailorability, as measured by the subjective ranking of jacket appearance, with the KES parameters of the fabrics the jackets were made from. The result confirmed the validity of the initial premise, that tailorability could be predicted from fabric hand.[5,6]

Accordingly, fabric finishers received new specifications from suit manufacturers. To meet specifications, they sometimes asked weavers for assistance. And so began a dialogue among the different segments of the industry. The benefits showed up rapidly at plants that adopted KES parameters as specifications for incoming fabrics. Manufacturing yield improved significantly. Seconds due to mechanical defects practically vanished.[7] Suit pricing became an explicit function of KES parameter values.

KES instruments were designed from the careful observation of industry experts while they expressed their tactile perceptions.

The success of the KES method rested on the experimental procedure used to measure fabric mechanical properties. KES instruments were designed from the careful observation of industry experts while they expressed their tactile perceptions. This deliberate attempt to approximate manipulations by human hands had no precedent. Earlier efforts to generate a predictive capability had failed because the mechanical properties had been measured under irrelevant conditions. For example, determining bending rigidity by the cantilever test, in which the fabric is supported at only one end, does not simulate the experts' action of grabbing the fabric with both hands. The KES bending tester simulates this action well.

About a thousand individual KES instruments are in operation across various segments of the industry to characterize not only woven and knit fabrics but also nonwoven fabrics, papers, films, and other sheet-like materials.[8] The instruments' rather slow adoption, particularly outside Japan (250 over the last fifteen years), stems from two factors. First, their sophistication calls for skilled operators and technical guidance, which make them better suited for a research environment. That limitation prompted Australia's CSIRO Division of Wool Technology to develop the simpler, more rugged FAST instruments for use on the factory floor. The KES manufacturer responded recently by introducing fully automated versions of the instruments. Second, some experts, mostly foreign, have been skeptical about the feasibility of translating subjective qualities into a combination of quantitative mechanical or physical properties.

1.1.2. More about Fabric Hand

With their merits as hand and tailorability predictors demonstrated, KES parameters were used to define and optimize process variables. Today they help assess quantitative changes in yarn spinning and texturing conditions as well as fabric construction and finishing procedures, be it dyeing, chemical surface treatment, or calendering. Their sensitivity also allows the monitoring of quality retention during garment life, in particular the impact of mechanical fatigue, wash cycles, and dry cleaning. In addition, they have proven valuable in new product development by determining how close an imitation is to its goal,[2–4] as for instance with natural fiber-like synthetics (fig. 1).

Objective specification of product qualities now extends to nonwovens, hosiery, bedding, home furnishings, automotive upholstery, flooring materials, leather, and even films. Consistent with the two-step method outlined above, the operating conditions of the KES testers vary with each class of materials, since they seek to simulate the mechanical deformations experienced by the products in use or at the time the experts express their perceptions.

1.1.3. Warm Touch

Industry experts adapted the KES method to the various fabric classes mentioned so far with relative ease but ran into difficulty with shirting and blousing. The overall quality could not be satisfactorily predicted without a thermal component, the instantaneous rate of heat transfer, which reflects how warm a fabric feels to the touch. An additional KES tester[9] simulates that process by measuring how much a metal plate preheated to skin temperature (32°C) has cooled down 0.2 seconds after contacting a fabric in thermal equilibrium with the environment (20°C). For example, staple-based fabrics (such as jersey knit underwear) entrap more air and have fewer contact points with the skin. Hence, they are poorer heat sinks and feel warmer than flat continuous filament counterparts with the same chemical composition (such as satin jacket lining).

Though intended for overall hand quality prediction of shirting and blousing, this new instrument can also measure fabric heat loss in a steady state as well as fiber thermal conductivity in the longitudinal and transverse directions. With the addition of a “sweating” plate, forced-air circulation, and fabric spacers, the tester can characterize thermal properties of simulated garment assemblies. Its use now extends beyond apparel fabrics to a variety of sheet materials, including bedding and home furnishings.

1.1.4. Drape

Like tailorability and fabric hand, drape used to be described only qualitatively. It, too, can now be quantified as a result of a MITI project (Part 2, Sec. 3.3.1) designed to demonstrate the feasibility of automating tailored garment manufacture. The project identified moiré topography and contact profilometry as the most promising techniques.[10]

Moiré patterns are optical interferences resulting from the overlay of two repetitive structures in such a way that the line elements of one are nearly superposed on those of the other. Though known since ancient times and studied by British physicist Lord Rayleigh in the nineteenth century, it is only in the second half of the twentieth century that the phenomenon was recognized as having merits for analytical purposes. The interest in moiré patterns is nowhere greater than in Japan, which even has a professional organization, the Japanese Moiré Fringe Society. Since the early 1970s, physicians have used commercial moiré cameras[11] for early detection of scoliosis among school-age children.[12] The 1980s saw their introduction to the textile field. The two repetitive structures used here are a reference grating placed in front of the camera and its projection onto the nonplanar surface to be characterized. The procedure exhibits two important accomplishments: (1) measurements are performed without contacting the object's surface, and (2) they are not restricted by object size or movement.

Application of moiré topography to the quantification of drape involves the following steps: (1) placing the garment—say, a skirt—on a mannequin rotatable by 45° increments, (2) obtaining the moiré patterns at the eight angles of view corresponding to a complete turn, and (3) scanning them to get a three-dimensional representation of the skirt (fig. 2 and 3). Manufacturing conditions required to match that representation can then be specified using a skirt design based on triangular finite elements (fig. 4).[13] Such elements include the skirt pattern, part sizes, fabric weight, and key KES fabric parameters. The approach also permits visualization of how changes in these conditions affect drape. In a related application, moiré patterns of representative Japanese women's bodies led a lingerie manufacturer to redesign fitness apparel and brassiere lines. Walk-in booths equipped with mirrors and a moiré camera even help customers in department stores see how well articles fit their bodies.[14]

Walk-in booths equipped with mirrors and a moiré camera even help customers in department stores see how well articles fit their bodies.

The technique is inadequate when parts of the surface are inaccessible to the camera or reference grating projection. In such cases, a profilometer of MITI's design is used, which has an articulated arm that keeps constant contact with the surface, thus giving a three-dimensional model with the desired accuracy.

Subsequent quantification extended to dynamic drape—that is, the conformation of a skirt during body motions. Emerging correlations tie the dynamics of the moiré patterns obtained with oscillating mannequins to the dampening of the shear and bending properties of the fabric, which are measured by fatiguing it at the same oscillation frequencies on the corresponding KES testers.[15]

1.1.5. Wrinkling, Bagging, and Seam Puckering

Wrinkling, bagging, and seam puckering pertain mostly to garment modifications that result from repeated deformations in wear. The first is self-explanatory; the second shows up at elbows and knees; and the third comes generally from shrinkage during maintenance cycles, though sometimes it appears during fabrication because of a mismatch between the mechanical properties of the fabric and those of the sewing thread.

Moiré patterns faithfully reflect these garment deficiencies. The affected areas are considerably smaller than those involved in drape. Since there is no need for sophisticated three-dimensional models of whole garments, electronic scanning is not required. Visual counts of the fringes—that is, the optical interference lines—and measurements of their spacings allow preliminary quantitative interpretation and guide process and product optimization.[16,17] Laser and ultrasonic scanning offer even simpler routes to determining the magnitude of seam puckering (fig. 5) and wrinkling with a resolution ranging from 0.5 to 1 mm.[18–20] All three quantitative, noncontacting mapping techniques have helped lay the foundations of a sewing science aimed at eliminating puckering by defining thread mechanical and shrinkage properties, sewing tension, and stitch density for a fabric that exhibits a given set of KES parameters.[21] Another objective is to spell out the impact of these variables on fabric stiffness and drape.[22]

A fiber producer, for example, has built an environmental testing chamber capable of reproducing any climate on earth, including wind, rain, snow, and desert insolation.

1.1.6. Garment Comfort

The advances in fabric mechanics responsible for the objective specification of hand and visual perceptions have encouraged investigators to take on another challenge—understanding the perceptions by other parts of the body, known collectively as comfort. A conjunction of elements favored such an effort: (1) a high sensitization of consumers to their physical environment, (2) a growing business opportunity for specialty apparel (Part 2, Sec. 2.2), and (3) the industry's increasing technical capability. The outcome has been a continuous flow of new products that cater to one of these perceptions. Claims generally rest on physical or mechanical property measurements performed on the wearers or in laboratory simulations of end-use conditions; both approaches call for novel facilities and instrumentation. A fiber producer, for example, has built an environmental testing chamber capable of reproducing any climate on earth, including wind, rain, snow, and desert insolation. Its size accommodates an automobile, and hence the evaluation of automotive upholstery, among other things. Thermovision cameras and miniaturized thermal/vapor sensors permit manufacturers to monitor body responses, which are used to support marketing. Consumers are left to infer improvements in the targeted perceptions, which are seldom measured under strict protocol conditions.

1.2. Modeling of Fabric Mechanics

The success reported above in objectively specifying fabric and apparel qualities provided the impetus for attempting to model relevant fabric deformations from their constitutive properties—that is, construction characteristics and yarn mechanical parameters.[23] As pointed out earlier, to qualify for clothing applications, fabrics must possess flexibility, low shear rigidity, and extensibility. These requirements are designed to allow the making of garments, which are three-dimensional assemblies, from two-dimensional parts, and to minimize their interference with body motions. Since all three are reflected in the KES fabric parameter values, the task was to develop models that predicted these values.

The approach involved the following: (1) defining the unit structural cells of plain woven and knitted constructions; (2) identifying and modeling the modes of deformation experienced by the yarns at their crossover points in each of these cells during fabric extension, flexion (bending), and shear; (3) determining yarn mechanical properties by using the corresponding KES instruments (Part 2, Sec. 1.1.1) and others conceived for that purpose; and (4) plugging these properties into the equilibrium equations of the models to generate predicted KES fabric parameters that could then be compared with the experimentally measured counterparts. The other novel KES instruments permit biaxial tensile and shear testing, and the determination of yarn (and fiber) torque constants as well as lateral compressibility.[23]

1.2.1. Deformation Mechanisms

Woven and knitted fabrics are assemblies of yarns that are interlaced and interlooped respectively. They are characterized by their yarn densities—that is, the number of ends per unit length and width of fabric—and by the length of the yarn crimps produced by weaving and knitting. Their flexibility results from their constituent yarns' and fibers' ability to slip against one another, since neither are bonded. Relative motions are therefore limited only by fiber-to-fiber friction. The same factors account for their low shear rigidity, which reflects the ease of changing the interlace angle. The extensibility in a biaxial tensile mode, which best approximates end-use conditions, involves straightening the yarns that are bent over each other at the crossovers. This action depends on bending rigidity. Extension takes place with or without diameter reduction, depending on the yarn's lateral compressibility. Finally, tensile rigidity comes into play. The complexity and additivity of these various mechanisms are responsible for the nonlinearity of most fabric mechanical properties.

Using yarn mechanical properties as predictors of KES parameters of identically constructed fabrics—and hence of the subjective qualities of these fabrics—is becoming a powerful tool in manufacturing optimization.

1.2.2. Model Validity

The agreement in several cases between calculated and measured KES fabric parameters appears to validate the approach. However, refinements are needed in a number of areas, especially in predicting the magnitude of the hystereses as a function of yarn or fiber composition and in modeling the shear and bending behavior of knits. In first approximation, the fabric tensile strength turns out to be equal to the total strength of the yarns oriented in the tensile direction, hysteresis coming from interyarn and interfiber friction, not from fiber viscoelasticity. Modeling the tensile deformation of knits is more complex because the looped unit cells stretch significantly more than the interlaced cells of wovens. That stretching, which involves yarn slippage and lateral compression at the crossover points, aligns the yarns before they are appreciably extended. Predicting bending and shear properties of woven fabrics appears equally, if not more, promising.

Already, using yarn mechanical properties as predictors of KES parameters of identically constructed fabrics—and hence of the subjective qualities of these fabrics—is becoming a powerful tool in manufacturing optimization.[24,25]

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Products

Fibers, fabrics, and apparel generally begin their life cycle as specialties, which command premium prices and are sold in small volumes.

Fibers, fabrics, and apparel generally begin their life cycle as specialties, which command premium prices and are sold in small volumes. At the time of their introduction, trade press releases and then the technical and patent literature disclose the concepts on which they rest. As sales volumes grow and the technologies enter the public domain, specialties soon face competition. To maintain or gain market leadership, producers resort to improving product specifications through unpublicized refinements. Even when these refinements are disclosed, they more often than not pertain to detailed process modifications that are outside the scope of this report. Such modifications should not be belittled, though, for historically they have provided the competitive advantage that allows specialty items to penetrate many domestic and foreign markets.

Commodities constitute the bulk of the business and will be dealt with first in this section. However, specialties will receive most of the attention because they stand at the technological edge and point to the future of the industry. For the sake of clarity, their manufacturing is outlined in each instance with a description of product features.

2.1. Commodities

Some product refinements are designed to achieve greater uniformity and improve manufacturing yields throughout the chain. Fiber producers, for example, offer yarns with ever-better downstream processability—that is, fewer breakdowns and dyeing defects in fabric making. Converters draw on the fundamentals emerging from the advances in characterization (Part 2, Sec. 1) to tighten fabric specifications and raise tailoring quality. These enhancements generally do not bring about novel functional features but merely translate into expanded ranges of applications or better economics. The ingenuity and fine-tuning on which they rest are illustrated by the three following developments involving modifications of a fabric-finishing procedure (low-pilling fabrics), a fiber chemical composition (metal-spun elastomers), and a fiber cross-section geometry (conjugate-spun hosiery).

2.1.1. Low-Pilling Fabrics

The high tensile strength of synthetics permits their processing at speeds of several thousand meters per minute and confers outstanding durability on their end products. However, that strength is a shortcoming in the surface abrasion process that occurs during garment wear. As a fiber breaks up, the two free ends that are generated tend to roll back in opposite directions and form two small balls, referred to as *pills*. These are generally larger with knits than wovens because of the greater separation between yarn crossover points that block the roll-back. The pills are unsightly, giving the garments a mottled appearance. The higher the original fiber tensile strength, the longer it will take for a second break to occur and let the pill fall off, thus restoring surface cleanliness. Ideally, therefore, the tensile strength should be low at this point to increase the probability of the second break.

This is exactly what a Japanese fiber producer claims to have done with polyesters. The approach involves producing melts of the viscosity required for acceptable spinning continuity by bridging polyester segments of low molecular weight with small bifunctional compounds during polymer preparation. The resulting fibers exhibit the high strength associated with regular polyesters of the same total molecular weight. They are processed downstream normally, wound up into yarns, and converted into fabrics. During fabric finishing, a chemical reagent breaks up the bridges, reducing the total molecular weight to that of the

Ecological and economic factors have driven producers to search for alternative polymer compositions.

polyester segments.[26] From then on, the fiber strength—which is a direct function of the polymer molecular weight—is lower, thereby facilitating the desired release of pills.

The concept of building up the melt molecular weight with bifunctional compounds originated in the United States, where it has been applied industrially for decades. The bifunctional compounds here lead to a spontaneous bridge breakup by hydrolysis when the filaments emerge from the spinneret. The fiber producer—not the fabric finisher—controls the process. However, the relatively low yarn strength obtained in the process places constraints on downstream processing, particularly annealing under tension and high-speed conversion into fabrics. The Japanese procedure eliminates these problems.

2.1.2. Melt-Spun Elastomers

Spandex fibers contain a minimum of 85 percent segmented polyurethane. As a class, they are one of the star performers of the industry worldwide. Lighter, more durable, and more supple than conventional elastic threads, they offer up to three times their restraining power and so are highly suited for foundation garments, swimwear, and hosiery. The past few years have seen their applications grow, as stretch appears to benefit an increasing number of less obvious applications, including suit tailoring, prosthetic articles, and diaper fasteners.

Ecological and economic factors have driven producers to search for alternative polymer compositions for two reasons: first, to make fibers from melts and do away with spin dopes based on organic solvents; second, to broadly penetrate the polyester markets. Ninety-five percent of spandex production is used in conjunction with nylon and cotton; only 0.5 percent with polyesters. This situation results from spandex's inability to (1) withstand the 120°C to 140°C aqueous environment required to dye homopolyesters and (2) prevent contamination with disperse dyestuff subliming from homopolyester articles during ironing, especially in the presence of steam. Until recently, commercial melt-spinnable offerings had been polyetheresters, which fell short of meeting all of the property requirements simultaneously. A new, carefully designed polyurethane-ester has recently made its entry and, according to claims, would fulfill them all.[27] If so, its potential impact on the stretch segment of the polyester business could be significant.

The new composition has half as many ester groups as current commercial polyetheresters. This reduction, achieved by increasing the molecular weight of diol and dicarboxylic acid, improves the thermal and hydrolytic resistance to the levels needed for union disperse dyeing with homopolyesters. Yet the increase in crystallinity accompanying that reduction is reportedly insufficient to hinder the recovery from deformation at normal temperatures. The recovery is supposedly superior to that of spandex at –30°C. Other properties, such as color fastness, chlorine resistance, light resistance, and shrinkage, are also rated superior to those of spandex. The disclosures do not reveal, though, the types of spandex used as the controls.

2.1.3. Conjugate-Spun Hosiery

Women's hosiery producers use an array of technologies to control durability, stretch, sheer, coloration, and thermal perception. One producer confers stretch by letting a conjugate filament heat relax and thus crimp as a result of the difference in potential shrinkage that exists between the two side-by-side polymer components. The concept was pioneered and commercialized abroad, but a series of incremental refinements by Japanese producers have raised the quality of their products above that of foreign competitors.

The latest enhancement employs a conjugate filament characterized by a polyamide sheath and an eccentric circular polyurethane core connected to the outer surface of the fiber by a neck of uniform width (fig. 6). A brief elaboration is in order to appreciate the sophistication of such a cross-section geometry.[28] Spinnability demands that two polymer melt viscosities be balanced. The eccentricity of the core is designed to maximize crimp development, as is its volume fraction (which is about 0.3). The polyurethane contains polycarbonate segments to reduce tackiness where the neck reaches the fiber external surface, so that the undrawn filaments do not fuse in the yarn bundle. The residual tackiness and an undesirable tendency toward filament splitting impose an upper limit on neck width. Elimination of the neck (i.e., letting the circular core contact the external surface directly) has proved uncontrollable. Specifically, fluctuations in the width of the core exposure zone turned out to impart an objectionable barré effect. Finally, the core is also lightly cross-linked to increase thermal stability.

2.2. Specialties

The specialty class of products stands out as the second major technical achievement of the Japanese industry complex, as much by its size as by its diversity. It has been the cornerstone of the strategy designed to gain worldwide textile leadership. This chapter presents the developments in specialties and the perceptions these products engender. In several instances, the basic concepts have two embodiments—one in fiber form, the other as a topical finish for application onto commodity base fabrics.

2.2.1. Color

2.2.1.1. Intensity Enhancement

Reflection of impinging colorless light by the external surfaces of dyed and printed fabrics attenuates the coloration intensity perceived by an observer. Reflection amplitude is a direct function of the smoothness or flatness of the fiber surface, and of the difference in the refractive index between the two media at that interface. Synthetics are, for the most part, significantly smoother than natural fibers, and thus have failed to give comparable color intensities. The effect is especially noticeable in dark-shade polyesters.

New commercial processes drastically reduce reflection amplitude, and thus enhance color intensity, by microcratering the fiber surface or reducing the index difference with a fabric finish that has a refractive index lower than the fiber's. In some procedures, the finish itself gets microcratered while curing.

The ability of black microcratered polyester to confer on formal wear the depth of shade of worsted is a measure of the technology's effectiveness.

- **Microcratered Fibers.** This product concept rests on the critical dimensions of surface microcraters characterized by depressions and spacings similar to wavelengths of light. Only by satisfying this criticality do the craters redirect a major fraction of impinging light rays toward the inside of the fiber rather than toward the observer (fig. 7). The desired structure results from melt-spinning polymer compositions containing homogeneous dispersions of silica particles of uniform size, then subjecting the fabric to alkaline finishing. The silica particles at the surface dissolve more readily than the polymer matrices in which they are embedded because of their greater sensitivity to alkali. Thus, microcraters are produced.[29–31] The particles inside the fibers remain unaffected, so the treatment leaves the tensile properties of the fibers or fabrics essentially unchanged. The technology, covered by product patents in many countries, including the United States, is at the base of various commercial continuous filament and staple offerings. The ability of black microcratered polyester to confer on formal wear the depth of shade of worsted is a measure of the technology's effectiveness. Besides visual benefits, the hands are crisper and drier because of higher static-to-dynamic friction coefficient ratios.

As with several textile developments, the microcrater concept has its origin in the natural world. Specifically, the unique structural features of the eyes of nocturnal insects were found in the U.K. in the 1960s to be responsible for their high visual acuity. Their ocular lenses exhibit regularly arranged papillary chitinous cone-shaped projections of height and spacing approximating the wavelength of light.[32] No such protuberances exist on the eyes of diurnal insects. These characteristics are believed to provide more surface to trap impinging light rays. The consequences are reduced reflection, which makes nocturnal insects less vulnerable to predators, and maximized absorption of weak light beams, which helps night vision.

Microcratered fibers have an outer layer with a refractive index gradient—its highest value being that of the fiber polymer at the bottom of the crater, its lowest being that of air at the peak of the projections separating the craters. The same applies to the ocular lens surface of nocturnal insects. The outer layer of microcratered fibers is like a stack of virtual finish layers, each infinitely thin, with an incrementally changing refractive index. Light reflection at the interface of two such layers is essentially nil, since the difference in the refractive index between two adjacent layers is infinitesimal.

- **Fabric Finishes.** Light beams reflected off air-finish and finish-fiber interfaces are out of phase and cancel out, thereby increasing coloration intensity, if the finish layer is a quarter wavelength thick and its refractive index is equal to the square root of that of the fiber. Commercial compositions coming close to meeting that condition include fluorinated polymers, silicones, and acrylic resins generally applied with binders and, possibly, cross-linking agents. When fabrics are cured to increase their durability, these suspensions shrink and produce something like a microcratered finish layer.[33] Sometimes the formulation even includes silica particles to generate actual microcraters after alkali etching.

The technology, used on commodity synthetics, is of greatest value with polyesters, since they have traditionally been the most difficult to dye. Only quality finishing mills use the technology, because rigorous process control is essential to the uniformity of color intensity. Because of their proficiency, these mills have taken the process beyond the premium formal wear market to cost-conscious applications like textured polyester school uniforms. Hand, in this case, is claimed to be unaffected.

2.2.1.2. Thermochromism

Microencapsulated thermochromic systems pioneered by the ink industry constitute the active element that received fiber and fabric finish embodiments. The systems comprise a colorless electron-donating chromatic organic compound, an electron acceptor, and a reaction medium generally made up of one or two components. Above the medium's melting point, one of its two components solvates the electron donor and the system is colorless. As temperature drops to the medium's solidification point, solvation ceases, and the electron donor turns to the electron acceptor, which produces a colored addition compound.[34,35] These processes are all reversible. The chemical structures of the electron donor and acceptors determine the colors. The reaction medium components, on the other end, control the temperatures at which the color appears and disappears, as well as the sharpness of these transitions and the color intensities. Incorporation of ordinary dyestuffs or pigments increases the number of color combination options. The chemistry of these systems is too complex to discuss in this report.

- **Fibers.** Constraints on spinning conditions set by the thermal sensitivity of microcapsules impose sheath-core-type structures. The sheath is made of a high-melting fiber-forming polymer (e.g., polyester or polyamide), and the core consists of a dispersion of microcapsules (5 to 20 µm) with epoxy/amine resin walls in a low-melting matrix (e.g., polyolefin, polyamide, or polyester). Because of that sensitivity, the sheath must cover at least 80 percent of the fiber's surface and constitute 25 to 90 percent of the fiber's weight.[36] This composition also ensures mechanical durability and light stability. Preferred fiber cross-section geometries include anywhere from one to four cylindrical cores or a tubular core sandwiched between a sheath and an inner core of higher-melting polymer.

  The novelty value of this technology was first commercialized in casual wear (shirts and swimsuits) and accessories. Later, thermochromic systems that turned black in cold weather enhanced the capability of ceramic-modified apparel, primarily skiwear (fig. 8), to convert solar light into infrared radiation (Part 2, Sec. 2.2.4.3). Recent research has identified infrared-absorbing electron donors that become effective as they turn colored at the reaction medium solidification temperature.[37] A variant, confined to the novelty market, relies instead on photochromatic systems that change from colorless to blue when exposed to ultraviolet light.

- **Fabric Finishes.** Compositions of the thermochromic systems and applications are basically the same as those already described. However, the finishes contain binders and the capsules are smaller (3 to 4 µm)—two features designed to confer better durability.[38] Commercial offerings exhibit a broad range of colors.

In a continuing search for novel coloration effects, a fiber producer found inspiration in some species of South American morpho butterflies.

2.2.1.3. Brilliance

In a continuing search for novel coloration effects, a fiber producer found inspiration in some species of South American morpho butterflies. When viewed perpendicularly, the wing faces of one species show a striking transparent cobalt blue with metallic luster. With others, the colorations are deep red and green. As the angle of view decreases, so does the luster and they all turn brown. Moistening with a liquid of high refractive index, like water or alcohol, also changes the colors to brown, but drying restores the original brilliance. This subtle effect results from a combination of reflection, refraction, and interference that occurs in scalar structures consisting of parallel thin plates of even thickness (about 0.7 µm apart) and perpendicular to the face plane (fig. 9). Both sides of these plates display seven to ten longitudinal finlike ridges at 0.2-µm intervals. The backs of the wings and discrete portions of the faces, which are brown and without luster, also reveal reticular patterns, but with none of the above parallel arrangements.[29,39]

A commercial product mimics the face wing features with polyester yarns of bicomponent ribbonlike cross-section filaments having high aspect ratio and transverse differential shrinkage. The yarns are loosely consolidated to permit the filaments to acquire thirty to fifty twists per centimeter and to align themselves by shrinkage during fabric finishing conducted under low tension. The continually changing angle between the filament flat surfaces and the plane of the dyed fabric imparts depth and brilliance through multiple internal reflections and refractions, somewhat akin to those occurring in the butterfly wings. The richness, softness, and drape of such fabrics make them uniquely suited for topweight women's wear.[40]

2.2.2. *Odor*

2.2.2.1. Fragrance

Exploration of fragrance potential started in the late 1980s as a way to individualize textile perceptions and possibly reduce personal stress. To the surprise of many, a limited market test of accessories, primarily scarves and neckties, finished with a few microencapsulated flower fragrances confirmed the merits of the idea.[41] From then on, the

Many technologies today fight offensive odors in textiles with different levels of success.

development grew rapidly with both fiber and topical finish embodiments. The list of end uses lengthened to include apparel of various kinds, hosiery, home furnishings, bedding, and automotive upholstery. The range of active ingredients also broadened beyond scents to include mosquito repellents, skin care adjuvants, and even tree extracts.

- **Fibers.** The products are mostly variants of structures with a polyester sheath and a polyolefin core. The sheath is designed to prevent the loss of fragrance or other active ingredient, which is not microencapsulated but only dispersed in the core matrix. The loss would otherwise occur both at the spinneret exit, where temperatures are in the 100°C to 200°C range, and during storage before use. Further precaution is taken by ensuring that no part of the core reaches the fiber's external surface. Preferred morphologies consist of two to six cylindrical cores positioned tangentially around a coaxial cylindrical hollow that should not exceed one-fifth of the fiber's cross-sectional area (fig. 10). The hollow serves as the conduit for the release of the active ingredient and, for that reason, tow cutting into fiberfill-type staple is deferred until final fabrication. Kept sealed, there is no loss after six months. In open air, a little less than half escapes.[42–44]

  Prime applications are in scented bedding and home furnishings, particularly with forest tree extracts. Medical research on the quality of sleep based on patterns of the brain's α-waves indeed suggests that breathing pinene, for example, while resting has a relaxing effect.

- **Fabric Finishes.** The active ingredients are microencapsulated (5–10 μm) into polyurethanes or urea-formaldehyde resins formulated to withstand printing, padding, jet spraying, and heat setting, yet weak enough to rupture by friction during wear. Silicone or epoxy-modified polysiloxane binders are needed to give the finishes durability during washing and dry cleaning. Weight pickups of a few percent apparently leave the hand of fabrics unaltered. Fabric strips with extra fragrance loadings are sewn in critical garment spots, for example, armpits and crotches. Refinements in microencapsulation and binder chemistry are brought to bear as this development matures. Inorganic fragrant powders are now also added as active ingredients.[45]

2.2.2.2. Antimicrobial Action

Many technologies today fight offensive odors in textiles with different levels of success. The number of applications continues to grow and now includes all skin-contact end uses—legwear, footwear, lingerie, babywear, sportswear, health care products, and, more recently, home furnishings. The business grows annually by double-digit percentages, and the industry has a lot of players. In fact, some of the products might already be considered commodities.[46] Chemistries are many and beyond the scope of this survey. Suffice it to say that the Textile Products Hygienic Processing Association has approved over sixty agents in ten categories, the three most important being (1) inorganic compounds, such as metal silicates and zeolites, that produce reactive oxygen to act much like ozone in sterilization; (2) metals coordinated with fiber substrates to react with the lone pair of electrons of offensive ammonia, amines, and mercaptans; and (3) quaternary ammonium salts, which destroy microbial cell walls.

- **Fibers.** Among the most successful products is a family of polyester and polyamide yarns. These yarns have round cross-section staple and filaments, each containing two polymer phases. One phase contains zeolite particles with well-anchored metal ions. That phase is spun into four discrete volume elements surfacing as four bands along the fibers. The additives are active against bacteria, molds, and offensive chemicals. The amount of metal ions bleeding with time is low enough for the products to be considered safe. More than two-thirds of the particles survive thirty wash cycles. Tensile properties and textile processability are unaffected.[47] The same types of agents are also found in some acrylic fibers.

  Typical of the second category of agents is a staple with a polypropylene sheath and a polyester core. The sheath contains copper powder to handle sulfur derivatives, and the core has a high concentration of carboxylic groups to capture amines.

- **Fabric Finishes.** Property limitations on some agents and the ease of commercialization militate at times in favor of topical treatment approaches. For instance, sprinkling zeolite particles on nonwoven webs followed by hot calendering embeds them adequately into lower-melting interspersed binder fibers. In other instances, fabric finishers call upon microencapsulation technology, which is at the basis of many specialty products reviewed here.

2.2.3. Sound

Complete simulation of silk with polyesters has come one step closer to reality with the introduction of an odd cross-section fiber that imparts silklike scroop and rustle to woven fabrics.[48–50] Japanese consumers had conceded that technological advances had made it increasingly difficult to distinguish the hands of the simulations from those of the genuine articles, as corroborated by KES parameters (Part 2, Sec. 1.1.1). However, distinguishing the fabrics by sound had remained easy.

Scroop is a low-frequency bass sound perceived with the ear close to the source, while rustle is more of a soprano hiss characterized by high frequency. Both can be duplicated with a laboratory instrument that rubs fabric against itself at about 10 cm and 50 m per minute, respectively. The sounds result from stick-slip phenomena associated with differences between the static and dynamic friction coefficients. Some silk fabrics are intentionally roughened by acid treatment or application of an abrasive agent.

The new polyester fiber has a trilobal cross-section geometry with a longitudinal microgroove, or side slit, at the apex of each lobe. This configuration acts like a tuning fork when rubbed by an adjacent fiber (fig. 11). The difference between the two friction coefficients is a direct function of the microgroove width and depth. To match the differences shown by the genuine silk controls, the width and depth of polyester knockoffs must be between 0.1 and 0.3 µm. If they are smaller, the sound is inaudible; if larger, it is undesirably grainy. Additionally, this fiber structure confers silklike luster and depth of shade (Part 2, Sec. 2.2.1) as well as hand.

A major polyester producer offers a 35 percent void-containing fiber that provides either the same thermal insulation and cover factor at about two-thirds the weight of the solid-fiber controls or lower air permeability and higher cover at the same weight as the controls.

2.2.4. Warmth

2.2.4.1. Ultralow Density

Void fractions of low-density fibers, such as those used for fiberfill, carpets, and water-absorbent products, generally do not go much beyond 10 percent. When the value is higher, the fibers tend to flatten, or even collapse, during processing. Luster becomes excessive and depth of shade is reduced (Part 2, Sec. 2.2.1). Fibers with up to 40 percent void fraction have appeared on the market lately and do not show these limitations. The process behind them involves spinning variants of sheath-core structures and then removing the cores, but not before fabric finishing. This method avoids conditions that might cause flattening.

A major polyester producer offers a 35 percent void-containing fiber that provides either the same thermal insulation and cover factor at about two-thirds the weight of the solid-fiber controls or lower air permeability and higher cover at the same weight as the controls. The voided core diameter is three times the sheath thickness. Stated differently, fabrics of such a fiber weigh no more than those of polypropylene, even though their polymer density is 50 percent greater. However, the high void fraction penalizes the depth of shade, so preferred end uses are colorless or pastel. Another group of products has as precursors C-shaped sheaths and alkali-soluble polymer cores reaching the external surfaces through a narrow longitudinal slit.[51] After drawing, these bicomponent filaments lend themselves readily to false-twist texturing or comingling. Subsequent alkali finishing solubilizes the core, which gives, for the first time, textured filament yarns with a void fraction in excess of 30 percent that are highly suited for thermal insulation applications. The filament core is then connected to the atmosphere via a narrow longitudinal slit, which imparts a springy feeling (fig. 12). Embodiments are either polyester or polyamide based.

In a variation of this process, the sheath is made of a blend of polyester and hydrophilic polymer. Alkali finishing not only removes the core but also introduces microcrazes and pores throughout the sheath. These rapidly absorb liquid sweat from the skin and transport it to the hollow core. Here, the product features dryness rather than thermal insulation.[52]

2.2.4.2. Electroconductivity

A polyester core filament coated with a conductive polyurethane containing from 30 to 50 percent carbon black is now available as a heating element operating in the vicinity of 80°C under 20 to 200 volts. Being essentially organic in nature, the element breaks up if the temperature accidentally reaches 140°C. Its infrared radiations can warm the human body, since they peak around 8 to 10 µm—a point at which the skin shows high transparency. The high flexibility of these filaments, compared with nickel-chrome wire, allows them to be knit and woven and to withstand thousands of bending cycles. Their lightness and abrasion resistance are also assets, particularly in apparel and semitextile applications. Such applications include winter, fishing, diving, and riding wear, as well as gloves and socks. Additional end uses are found in health care products, such as supporters and foot warmers.[53]

Another development with a similar goal produces air-jet consolidated spun yarns containing equal amounts of aramid fibers and long ultrafine steel fibers of specified resistivity, both obtained by draft-cutting continuous filament bundles. Any yarn cross section must have at least ten steel fibers to ensure enough contacts for yarn conductivity. Manufacturers claim that the products possess greater flexibility and flex durability, as well as higher temperature resistance, than those coated with carbon black.[54]

2.2.4.3. Light-to-Heat Conversion

MITI's Sunshine project identified carbides of the group IV transition metals as potential coating materials to increase the efficiency of solar panel heat exchangers. Zirconium carbide was preferred, partly because of its ability to absorb and convert the visible part of the solar spectrum into heat (infrared radiation) while reflecting any such radiations above 5 µm.[55] Latching onto these findings, and a good illustration of "lateral" thinking, a fiber manufacturer decided to modify textiles with particles of zirconium carbide to heat the body and, at the same time, insulate it by radiating back body heat radiation peaking around 8 to 10 µm (fig 13). When thermochromic additives are present (Part 2, Sec. 2.2.1.2) and turn black at the desired end-use temperatures, they boost the magnitude of the effect. Current applications include skiwear, sportswear, workwear, home furnishings, and even geotextiles to protect young shoots from night frost. Girls' schools are gradually adopting swimwear of this type because the wearer feels warmer coming out of the water and the fabric dries faster. Laboratory fabric characterization and temperature measurements in wear tests have placed the development on a quantitative basis. Once again, the concept has been reduced to practice in the form of fibers and finishes for fabrics.[56]

- **Fibers.** The sheath-core structure is a must, with the zirconium carbide particles confined to the core because of their abrasiveness and gray-black coloration. Failure to have a protective sheath would damage the spinning equipment. The sheath thickness is critical to let solar light reach the buried particles while minimizing interference from the gray-black coloration when the end use calls for white. In fact, the grayish cast prevents bright coloration by dyeing and has led to the identification of alternative white ceramic additives. These additives' efficiencies as heat generators unfortunately do not match that of zirconium carbide. Removing the sheaths by hydrolysis during fabric finishing (fig. 14) maximizes heat generation in applications that render the yarns invisible, as in some apparel linings and home furnishings.[57] Although the ceramic particles lend durability to the fibers, process flexibility and economics favor loading them in topical fabric finishes.

- **Fabric Finishes.** Particles can be of larger dimensions, and thus cheaper, than with fibers because of the absence of spin pack filtration. The amount can also be larger, since spinnability is not required. Binders are typically polyurethanes, with or without polyisocyanate, and polyacrylic esters. They are essentially similar to those used in other developments described in this report.

Finishes applied to the back (inner) side of the articles give unrestricted freedom of coloration to the face fabric but then act more as insulators than as visible-to-infrared radiation converters because of the face fabric shielding effect.[58,59]

2.2.5. *Coolness*

2.2.5.1. Ultraviolet Reflection and Absorption and Infrared Reflection

The sun-shielding effect claimed for some polyester light summerwear introduced in the early 1990s rests on experimentally measured cooling ability and sunburn prevention. The first results from the ability to reflect or scatter visible and infrared (IR) radiations imparted by ceramic additives with refractive indices significantly greater than those of the yarns they modify. The greater the difference, the greater their effectiveness, which is also a function of particle size and surface roughness. Ceramics of choice, such as titanium dioxide and zinc oxide, also transmit less ultraviolet (UV) radiation than the yarns, thereby helping control sunburns. Even more effective sunburn protection is provided by organic molecular agents that are raised to higher energy states by radiation absorption. They subsequently return slowly to their fundamental levels, but since the energy changes are small, the body detects essentially no heat exchange. Additionally, the magnitude of sun shielding is a function of fabric tightness and yarn structure, with staple providing more protection than continuous filament. These ceramic modifications are found in shirts, blouses, and casual dresses, as well as hosiery.[60] Depending on ambient conditions, the temperature in the air space between the garments and body might be lower by as much as 6°C. Protective articles such as sun hats, sun umbrellas, tents, and curtains are also reported.

Depending on ambient conditions, the temperature in the air space between the garments and body might be lower by as much as 6°C.

- **Fibers.** Market offerings today go from staple to continuous filament yarns, nearly all polyester based, of odd cross-section or sheath-core structure.[61,62] Economics of the spun-in ceramic agents dictate that the particles be in the range of 0.5 to 0.7 µm, instead of 0.1 to 0.2 µm, to maximize reflection by suppressing destructive interference. The rationale for the odd cross section is also to maximize scattering, but this time by the fiber external surface. The sheath-core structure, on the other hand, permits an increase in the amount of ceramic agent without risking abrasion of the spinning equipment, since the agent is confined to the core. Because of their instability and ease of sublimation at spinning temperatures, organic UV absorbers enter only in the formulation of topical fabric finishes.

- **Fabric Finishes.** Considering their affinity for polyester fibers, organic UV absorbers are applied along with dyeing, but with cellulosics, resin binders are needed. Application techniques, in this case, follow those mentioned earlier—namely, padding and printing with or without microencapsulation. The most effective are mixtures of organic and ceramic active ingredients selected to reflect and absorb, but not transmit, radiation over a broad range of wavelengths.

2.2.5.2. Hydrophilic Finishes

For a long time, these compositions have been used to wet hydrophobic surfaces (Part 2, Sec. 2.2.6.1). However, the past five years have seen growing patent activity and commercialization of products, primarily pantyhose, claiming a "body heat pulling action" that results from the vaporization of the sweat picked up by the finishes.[63] Temperature and relative humidity measurements and thermovision examination conducted during rigorously controlled wear tests correlate the magnitude of the heat loss with the fiber moisture regain. The finding has prompted the development of more hygroscopic nylon yarns by incorporating alkali metal carboxylic and sulfonic salt groups or polyalkylene oxide units.[64,65] A recent variant uses elastic core yarns covered with a hygroscopic nylon or cellulosic fiber for leg support. The cooling in this instance comes not from the finish but from the sweat-loaded surface fiber component.[66] The high fiber surface-to-volume ratio of women's hosiery might make it the article of choice for capitalizing on this heat-of-vaporization effect.

Garments that guarantee dryness during exercise are highly sought after by the sportswear industry.

2.2.6. Dryness

Garments that guarantee dryness during exercise are highly sought after by the sportswear industry. During the past decade, an array of such garments tailored to a variety of end uses have emerged. These items fall into two broad categories: those that offer rainproofing and those that do not.

Without Rainproofing

The human body, even at rest, continuously releases sweat, which vaporizes at the skin surface. As activity increases, so does the amount of sweat. When the sweating rate exceeds the permeation rate of a fabric, the microclimate zone between the garment and the body gets saturated. Liquid sweat appears and, with it, a string of undesirable perceptions ranging from wetness to clamminess. Products are now available that increase the permeation rate with various levels of success, thus delaying saturation and attendant discomfort. The order of the following approaches reflects their growing efficiency at pumping the sweat away from the skin into the garment.

2.2.6.1. Wicking

- **Hydrophilic Surfaces.** The wetting angle of water on hydrophobic synthetic (mostly polyester) fibers can be lowered by increasing the surface concentration of carboxylic groups. Finishers rely on the application of hydrophilic finishes (cured, cross-linked in situ, or grafted), controlled alkali-catalyzed fiber surface hydrolysis (Part 2, Sec. 3.2.2.1), or low-temperature exposure to plasma following polyethylene glycol pretreatment.[67,68] The results are not only improved wettability and oily soil release but also a reduced propensity for generating static electricity.

- **Odd Cross-Section Fibers.** An alternative approach modifies the fiber cross-section geometry to allow close packing. In conjunction with surface water wettability, this process creates capillary forces in the interfiber volume that are sufficient to wick away liquid sweat. Cross sections of choice for sportswear have the shape of C (Part 2, Sec. 2.2.4.1) and those for lingerie of L (fig. 15) and Y.[69] The inherent hydrophilicity of some polyamides eliminates the need for a surface treatment to confer the required water-wettability.

2.2.6.2. Hydrophilicity Gradient

This ingenious technology followed pioneering work carried out in Sweden in the 1970s, which established the benefit of wearing, in northern climes, a thin, hugging hydrophobic knit garment against profusely sweating skin. However, a loose, water-absorbent outerwear needed to be present to pick up the oozing sweat droplets.[70] The convection created by the relative looseness of the outerwear speeded the vaporization of the absorbed sweat. To overcome the technical and styling limitations imposed by such garment systems, a Japanese firm combined the two garments into one. It engineered a single knit garment with the hydrophobic yarn component dominating the back side and the hydrophilic one dominating the face.[71] The gradient in cotton or rayon is therefore steep across the fabric, going from essentially 0 to 100 percent, with no perception of clamminess on the body side (fig. 16). Measurements of the relative humidity in the microclimate zone during physical activity document the effectiveness of these constructions. The constructions are clearly different from those based on two fabric plies tied together, which had been available for years. Since their uniqueness rests on fabric engineering design, the embodiments allow the use of commodity yarns.

2.2.6.3. Fiber Microporosity

Hollow microporous polyester fibers exhibit unusual absorbency properties. The micropores, ranging from 0.01 to 3 µm in diameter, are formed during fabric finishing by dissolving a hydrophilic additive.[72,73] Residual amounts of the additive most likely furnish the wettability needed for sweat to enter the fibers and migrate at a rate of 1 cm per minute inside the hollow core. The core constitutes more than 10 percent of the fiber volume (fig. 17). Once absorbed, the sweat is no longer in contact with the skin, so the fabric feels dry, while cotton garments feel clammy. Furthermore, the absorption takes place without change in fiber diameter, so fabric air permeability is unaffected. Cotton counterparts plug up as a result of swelling. Drying cycles are also shorter because sweat or water is stored in bulk, not intermolecularly as with cotton. An additional asset is that the high total void content of such fibers confers good thermal insulation properties when dry (Part 2, Sec. 2.2.4.1). Spinning conditions seek to maximize absorbency—that is, micropore and hollow-core volume fractions—while satisfying end-use mechanical durability requirements. This delicate balance, plus process economics, confines these morphologies to yarns used in the fill direction of woven fabrics where they are not load bearing. One fiber producer claims to have cut the amount of hydrophilic additive by 60 percent, to below 2 percent by weight, with the incorporation of an agent that regulates microvoid formation. The relatively low tenacities of these fibers also confer good pilling performance.

These microporous hollow fiber structures currently are being evaluated in the reverse mode for medical therapy. In this application, they would dispense drugs by epidermal absorption[74] with apparently less irritation and skin swelling than occurs with impregnated polyester film patches. Fiber size and yarn twist would determine the amount of micropores available and hence the delivery dosage. The first application is expected to involve heart drugs.

With Rainproofing

Ensuring impermeability calls for fabric micropores, or interstitial spaces, that do not exceed 10 µm in diameter. This measurement prevents penetration of drizzle droplets, which, on average, are about ten times as large.[75] The micropores must also be long and have hydrophobic walls to raise entry pressures. Maximizing vaporized sweat permeation to the atmosphere, on the other hand, demands wide and short micropores—hence the need to optimize their widths and lengths. These demands are satisfied in two broad families of products: one based on membranes, the other on high-density fabrics.

2.2.6.4. Membranes

Breathable impermeable outerwear is mostly based on single nylon or polyester shell fabrics coated with a microporous polyurethane membrane (fig. 18) via one of two procedures.[76–79] The first is lamination of a polyurethane film containing a dispersed phase that is leached out during fabric finishing to create the micropores. The fineness and uniformity of the dispersion prior to film formation determine the width of distribution of the micropore dimensions. In the second, in situ coagulation replaces film lamination. The finishing sequence from there on is similar, the micropores being formed by the leaching of the dispersed phase. Variants include (1) different pore sizes (and hence water entry pressures) designed for specific outdoor activities; (2) high-stretch polyurethane formulations, as for skiing; (3) thermal-insulating particle additives (Part 2, Sec. 2.2.4.3); and (4) subdenier fabric bases. The drapability of these garments contrasts with the relative stiffness and paperiness of the functionally equivalent Gore-Tex counterparts that pioneered the concept of breathable impermeability two decades earlier. The active member in Gore-Tex is also a membrane, a fibrillated polyfluoroethylene film. Because of its low abrasion resistance, this film had to be sandwiched between two shell fabrics—hence the lower pliability.

Nonporous hydrophilic polyaminoacid membranes also transport vaporized sweat effectively but via molecular diffusion. Addition of some polyurethane is necessary to increase their extensibility. Producers claim that microporous membranes of such compositions further raise permeability by relying on both mechanisms (i.e., microporous and molecular diffusions).[75] Other refinements include applications of such hydrophilic compositions on top of microporous polyurethane membranes to prevent pore plugging by soil particulates, skin care agents, and laundry detergents.

Vaporized sweat escapes into the atmosphere at gradually increasing rates (up to 100 percent) as the air temperature of the microclimate zone rises past the glass transition point during exercise.

A third type of membrane, the latest to enter the market, is made of smart polymers characterized by intermolecular spaces reversibly opening and closing at their glass transition temperatures.[80–82] Coatings of such polymers are formulated to initiate this molecular relaxation process around body temperature. Under the circumstances, vaporized sweat escapes into the atmosphere at gradually increasing rates (up to 100 percent) as the air temperature of the microclimate zone rises past the glass transition point during exercise. The elastic modulus of the preferred polymers must decrease by at least a factor of 100 over the 20°C range centered on the glass transition temperatures. The decrease reflects the gains in the degree of molecular relaxation–in other words, of the intermolecular space opening. When exercise ceases, the coatings close up, supposedly helping body heat retention. In short, producers claim that these materials perform like human skin. The first commercial compositions are polyurethanes having low molecular weight polyols—one of the two initial reagents, the other being a diisocyanate—and high contents of chain extenders.

2.2.6.5. High-Density Fabrics

Refinements of the high-density fabric concept have imparted water repellency without resorting to the use of any of the above membrane technologies. Ultrafine hydrophobic filaments, 0.3 to 0.7 denier, in combination with novel fabric constructions, loom developments, and finishing procedures—required by the inaccessibility to dye liquors—produce the required filament or yarn packing and coloration flexibility. Not only is instantaneous water resistance reportedly high, but so is its durability to maintenance cycles.

A fiber producer has come up with a breathable polyester woven fabric from which water rolls off like mercury by emulating the microscopic roughness and wax-like coating of the lotus leaf.

Finally, a fiber producer has come up with a breathable polyester woven fabric from which water rolls off like mercury by emulating the microscopic roughness and wax-like coating of the lotus leaf. Water beads on the leaf surface because it lies either on air trapped underneath in microdepressions or on the waxy hydrophobic micropeaks (fig. 19). High-shrinkage subdenier filaments are again woven in tight constructions that are then dyed, bulked by a procedure creating uniform microscopic dents, and finished for water repellency. The fabrics never wet, even in downpours, and retain nearly all of their resistance to water after thirty washing cycles. This performance exceeds that of any incumbent products.[83,84]

2.2.7. Touch

2.2.7.1. Natural Fiber Simulation

For a long time, the goal of synthetic fiber producers was to come up with novel functional features while duplicating natural fiber aesthetics. Their offerings therefore consistently exceeded 1 denier per filament or about B5m in diameter. They and their downstream partners, the weavers, knitters, and finishers, had an array of variables at their disposal to reach their goal of (1) fiber composition, (2) fiber length (continuous filament versus staple), (3) fiber diameter and cross-section geometry, (4) yarn bulk (flat versus crimped), (5) fabric construction, and (6) fabric surface characteristics. Surface characteristics received exceptional attention in Japan, where finishing has moved from an art to a science (Part 2, Sec. 3.2). Alkaline, topical, and mechanical finishing turned out to be essential to the successful simulation of silk, cotton, and wool aesthetics with polyesters, polyamides, and acrylics.

2.2.7.2. Subdenier Fibers

Fear of process difficulties, and thus lower yields, had discouraged producers from attempting to commercialize subdenier yarns. This fear did not prevent individual polyester subdenier fibers, in the range of 0.1 to 0.5 denier, from entering the market outside Japan nearly four decades ago. These materials went directly into nonwoven webs used to reinforce polyurethane matrices sold as moisture-permeable leather substitutes. The desire for diversification of continuous-filament yarns led producers to revisit the issue and finally break the denier barrier in earnest around 1980 with two approaches: direct and conjugate spinning. Today, the Japanese practice both and a third, more recent route, involving mechanical fibrillation in situ of filament yarns already incorporated into fabrics. Producers outside Japan have pretty much confined themselves, of late, to direct spinning to a minimum of around 0.5 denier. Consequently, most advances in subdenier technology, be they in production, fabric formation and finishing, or apparel fabrication, have originated within the Japanese industry. Taken together, these advances stand out far above those embodied in the other specialty products surveyed in this report, as much for their technological sophistication as for their business impact. Though not formalized to date, the designation of microfiber generally covers the range extending from 1 denier to 0.5 or 0.3 denier for nylon and polyester, respectively, while ultramicrofiber pertains to anything finer.

2.2.7.2.1. Direct Spinning

When introduced around 1980, direct-spun 1-denier nylon that was air-jet textured offered an attractive cottonlike hand in line with the market needs of the time. The polyester counterpart came a little later, at only 0.6 denier because of the inherently greater stiffness of the polymer. Today, the technology has probably reached its limit at 0.1 denier or about 3 μm in diameter.[85] Tactile aesthetics conferred by these yarns are totally new and without natural fiber equivalents.

Process criticality evidently increases with fiber fineness.[86] Spinning elements receiving particular attention include melt filtration efficiency, hole dimension uniformity, spinneret plate configuration, quenching profile, guide positioning, and filament oiling procedure (i.e., composition, design, and location of applicators). These precautions aim to reduce filament breaks at the spinneret, during draw from excessive or nonuniform oil pickup, and in yarn package formation. The extreme fineness has required combining low extrusion rates with high postdraw ratios and hence high wind-up velocities (upward of 4,000 m per minute). Commercial products are primarily continuous polyester filament yarns used for high-density woven outerwear. The patent literature, however, contains 0.1-denier nylon disclosures. The technology was recently extended to 0.4-denier staples for spun and filament-core yarns used in premium women's wear claimed to exhibit entirely novel visual and tactile aesthetics.[87] Two of these staple yarns are specialty variants—one being microcratered to enhance coloration depth (Part 2, Sec. 2.2.1.1), the other loaded with ceramic particles to enhance drape.

2.2.7.2.2. Conjugate Spinning

Conjugate refers to individual filaments, each containing two or more distinct polymer phases. The introduction of conjugate filaments goes back to the late 1950s in the form of self-crimpable, and hence bulkable, yarns. The difference in potential shrinkage between the two phases produced the crimps by heat relaxation during fabric finishing (Part 2, Sec. 2.1.3). The filament integrity was retained throughout, the two phases adhering strongly enough to withstand the crimping forces. The concept was then deliberately altered to have the filaments split in fabric finishing, by heating or gentle alkaline treatment, so as to generate finer components of various cross-section geometries that mirrored those of the spinning holes. These finer components shrank by different amounts, as before, and yarn bulk increased. But distinctly different hands resulted, which KES fabric characterization has categorized as "peach skin," "new silky," "new worsted," and "dry touch," depending on yarn size and fabric construction. Variants called for dissolving one of the two phases to obtain some of the finest components exclusively. Japanese fiber producers used these initial findings to make conjugate spinning a key element in their ultramicrofiber technology (Part 2, Sec. 3.1.1.3). Deferring ultramicrofiber generation until fabric finishing circumvents the difficulties experienced with wind-up and downstream handling of direct-spun yarns.

- **First Materialization.** Conjugate spinning received its first commercial validation in the early 1970s with the development of Ultrasuede nonwoven fabrics for apparel and semitextile markets. The multidenier continuous filament precursors, exhibiting the so-called sea-island configuration, consisted of parallel polyester filaments of 0.1 denier each immersed in a polystyrene matrix (fig. 20). Once laid down, they were stripped of their matrix by solvent action, and the leftover polyester fiber network was embedded in polyurethane. Mechanical finishing conferred a luxurious soft hand that simulated suede, cashmere, or grain, depending on fabric weight, thickness, and amount of polyester. The commercial success of these products to this day is testimony to their superiority. The technology is also used today to produce yarns for weaving.[88]

In a slightly different embodiment, another fiber producer chose to randomly mix the two polymers prior to spinning the precursor. Though the rest of the process was qualitatively similar, removal of the matrix gave discontinuous fibers ranging from 0.1 to 0.01 denier. Dissolving the dispersed fibers instead by selecting the appropriate solvent led to porous matrix-based continuous filaments.[89]

- **The Proliferation.** The opening of the subdenier field marked the beginning of a new era in the history of synthetics. Wide arrays of apparel and semitextile products have emerged because of the practically unlimited number of fiber design options. Major variables include polymer composition, size, and cross-section geometry of the precursor filament, and ways to distribute one polymer around the other—that is, the number, size, and cross-section geometry of the embedded fibers. The fineness easily reaches 0.01, 0.001, or even 0.0001 denier.[90] However, economics burdened with the costs of multipolymer spinning capability and of a finishing treatment, which may include polymer elimination or recovery steps, limit opportunities for premium end-uses. These expenses limit opportunities to premium end uses. Practically all Japanese fiber producers are players in the subdenier field.[91,92] Their success has contributed to their overall technological leadership and has prompted some Asian competitors to travel down the same route.

The opening of the subdenier field marked the beginning of a new era in the history of synthetics.

Four important yarn offerings, all based on filaments of about 2 denier, illustrate the scope of the technology.

1. With a polyester/nylon ratio of 7/3, the filaments of the first yarn split during alkaline fabric finishing into eight wedged polyester segments, each 0.17 denier, and a star-shaped nylon core of 0.6 denier. The star-shaped core is splittable by differential shrinkage into four wedged segments and a cross-shaped core (fig. 21). The yarns go into (1) needled nonwovens, which are the basis of a line of luxurious Ultrasuede-type products; (2) warp and circular knitted semitextile wiping cloths, which stand out for their ability to pick up dust because of the subdenier filament razor-sharp edges (fig. 22),

Another producer claims that ultramicrofibers show promise for artificial vascular grafts.

their large surface area, and their affinity for oil and aqueous stains[93,94]; and (3) breathable impermeable high-density woven fabrics (Part 2, Sec. 2.2.6.5) for sportswear, fashion apparel, and accessories, either in 100 percent form or blended with natural fibers and synthetic staples.

2. Filaments of the second yarn morphologically resemble those of the first, but the eight wedges are of nylon, and the eight-branched polyester core (of only 0.5 denier) dissolves during the alkaline finishing. Typically after such a finishing, a drawn 100-denier yarn comprising 50 filaments turns into a 70-denier yarn made up of 400 subdenier filaments. A variant includes a four-branched nylon core. These fabrics also go into apparel and filters that producers claim retain 90 percent of particles as fine as 0.5 µm.

3. The third case is a spin-off of the first. Wedges and core are of polyester but have different sensitivities to hydrolysis, so the 0.5-denier core dissolves during alkaline finishing.

4. Filaments of the fourth yarn have cross sections that mimic a sunflower or cosmos (fig. 23) and consist of three polyesters.[95] The core, which represents 35 percent of the weight, has a high-shrinkage composition. The petals, of 0.1 to 0.4 denier, range in number from six to twelve. They equal 45 percent of the weight and are of regular composition. The core-petal bond, accounting for 20 percent of the mass, easily dissolves when exposed to a base. The finished fabrics exhibit bulk, produced by the relatively high-denier and high-shrinkage core, together with softness conferred by the low-denier petals. End uses include sportswear, formal wear, and automotive upholstery.

Another producer claims that ultramicrofibers show promise for artificial vascular grafts. They exhibit higher biocompatibility than their thicker counterparts and greater ease of handling. Living cells apparently gather around them like small fish schooling around reeds and grow rapidly to cover the inner wall.[96]

2.2.7.2.3. Mechanical Fibrillation

The prior art of spun lacing, which entangles fibers in nonwoven webs by impingement of high-pressure water jets, provided the seed of this development. The application uses similar webs but of conjugate filaments. They first split under the water impact to give odd cross-section ultramicrofibers that then entangle each other. The smoothness, wovenlike drape, and overall hand result from the matrix freedom produced by the absence of bonding at the fiber crossover points. If need be, the overall strength can be raised and balanced by web cross-laydown. The products are amenable to standard finishing, such as dyeing, printing, and embossing. Semitextiles are targeted for this technology, with applications including reinforcement of thin artificial leather, wiping materials, and filters. The last two applications take advantage of the sharp edges and high surface area. Polyesters, polyamides, and polyolefins make up the polymer combinations most frequently encountered.[97] An interesting embodiment employs microvoided acrylic fiber webs thick enough to confine the fiber splitting to the surface layers, leaving the core unaffected. Besides an attractive balance of bulk, flexibility, and dimensional stability, the sheets exhibit hydrophilicity, which makes them well-suited for wiping aqueous fluids.[98,99]

2.3. Notes

Italicized words indicate trade names.

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Manufacturing

A strong manufacturing capability must be added to product and process insights (Part 2, Sec. 1) and innovations (Part 2, Sec. 2) to account for the emergence of a world-class textile technology in Japan. Commercialization of these innovations, which called for rapid scale-up of complex fiber production and fabric-finishing procedures, has already testified to manufacturing's flexibility and sophistication. This section covers advances in the making of fibers and yarns, fabrics, and apparel, and thus highlights two other aspects of Japan's manufacturing capability—productivity and automation. These realizations are not, for the most part, product specific; that is, they do not depend on fiber chemical and physical characteristics but rather on basic, often radically novel, production concepts. Their implementation spells out an ancillary need for skilled manufacturers of domestic textile equipment. Two of the six largest in the world are, indeed, Japanese; the other four are European, which makes for some competition.

3.1. Fibers and Yarns

3.1.1. Chemical Spinning

3.1.1.1. High Speed

Driven by the desire to lower cost and increase uniformity of synthetic fibers, eight producers participated in a six-year MITI-funded project[100] that ended in 1988. The project was designed, among other things, to raise polyester spinning speed beyond 6,000 m per minute. The whole process was revisited from ingredients to hardware design. Transfer lines were reprofiled to overcome filter pack plugging by gel particles. This plugging resulted from thermal nonuniformities. Small amounts of specific comonomers were found to help reduce plugging by disturbing polymer chain regularity enough to slow down crystallization during the molecular orientation that occurs in spin stretching. These advances, the subject of an abundant patent literature,[101] lowered the rate of yarn breaks by a factor of 100 (down to 1 or 2 per 10^8 m), making it possible to operate continuously at 6,000 m per minute for twelve days. They allow easy spinning in the range of 6,000 to 8,000 m per minute. The participating producers incidentally designed and built most of the equipment required for the improvements, including winders.[102]

As a result of the project, producers now can use either a pressurized compartment or a compressed air circulation arrangement to sequentially draw and false-twist texture polyesters at wind-up speeds exceeding 2,000 m per minute.[103]

Today, automation of the spinning process has reduced the amount of labor to the point where major producers have essentially unmanned polyester and nylon production lines.

Still another outcome of the MITI project was the clustered spinning of several (three to ten) yarn ends into a single spinning block. Circular airflow delivered perpendicularly to the spinning direction quenches the bundles of filaments, which may range from 0.8 to 8 deniers. Winding takes place at speeds anywhere from 3,000 to 8,000 m per minute. The bundles are distributed radially from the center of the spinneret plate.[104]

Today, automation of the spinning process has reduced the amount of labor to the point where major producers have essentially unmanned polyester and nylon production lines.[105] The Korean industry is following suit.[106]

3.1.1.2. Flexibility

The growth of the specialty fiber business prompted producers to increase the flexibility of their facilities. Streams of homopolyester coming from continuous polymerizers are now split into substreams, each modified by injecting additives, such as pigments, lubricants, and

Fluid-processing techniques (air, steam, or water) are broadly found in textiles worldwide as substitutes for mechanical devices offering high productivity and labor savings.

hydrophilic and antimicrobial agents, and each homogenized with in-line static mixers to produce parallel yarn ends of different compositions in small volumes.[107]

3.1.1.3. Two-Polymer Composition

The review of conjugate-spun products (Part 2, Sec. 2.2.7.2.2) outlined the spinning of filaments that contain two or more distinct polymer phases. Once in fabrics, the yarns are subjected to one of four finishing procedures, depending on their composition and targeted end use. The first, heat setting after bleaching and dyeing, does not alter the macrostructure of the filaments. It only stabilizes the dimensions of the fabric, which has the attributes brought about by the additive used in one of the two polymer phases (Part 2, Sec. 2.2.2.1 and 2.2.4.3). The second, heat relaxation, lets the individual filaments self-crimp according to the asymmetry and difference of shrinkage potential that exists between the two phases. It also confers stretch (Part 2, Sec. 2.1.3). The third, generally an alkaline treatment, dissolves one of the phases freeing the other (Part 2, Sec. 3.2.2.1). The fourth, mechanical fibrillation, subdivides the filaments longitudinally, capitalizing on a designed low-phase adhesion. The last two produce subdenier filaments, leading to novel aesthetics and functionalities (Part 2, Sec. 2.2.7.1).

The cross-section geometry of a conjugate-spun filament mirrors the shape, size, and relative position of the small orifices from which the various polymer streams emerge immediately prior to their coalescence. The range of numerical values these variables can take, not to mention the diversity of polymer compositions, opens the door to a practically unlimited number of combinations and thus products (figs. 24 and 25).

3.1.2. Jet Processing

Fluid-processing techniques (air, steam, or water) are broadly found in textiles worldwide as substitutes for mechanical devices offering high productivity and labor savings. The turbulence created by impinging products with fluids alters their structures in a desirable way. This action takes place inside jets, as with air in consolidating filament bundles by interlacing; bulking yarns by crimping and looping; or forming staple yarns by entangling and wrapping. In another series of embodiments, pressurized water exiting from jets generates subdenier filaments by fibrillation (Part 2, Sec. 2.2.7.2.3), forms nonwoven fabrics by fiber lacing, and propels fill yarns across warps on water-jet looms.

One Japanese textile equipment manufacturer pioneered a staple yarn formation process that uses two air-driven torque jets operating in series, but with the directions of their vortices opposite to each other. Fabrics made from such yarns tend to have a harsh hand and, for that reason, have been frowned on by the domestic market. However, other countries (the United States in particular), driven by the attractive economics, have commercialized the process and continue to seek improvements by fine-tuning feed fiber specifications.[108] With growing cost sensitization, the Japanese textile industry may soon start adding to the 2,500 machines already in use abroad.[109]

3.2. Fabrics

3.2.1. Weaving and Knitting

Placed between the fiber producers and yarn spinners at one end and the finishers and apparel manufacturers at the other, the weavers and knitters have little room for maneuvering. They are further constrained by the limitations of their equipment, which they do not make. The only area of innovation open to them is fabric design, and in that, Japan has traditionally scored an impressive record. Two accomplishments stand out. One is the development of subdenier fabrics, especially those of high filament- or yarn-packing density (Part 2, Sec. 2.2.7.2). The other is the engineering of sportswear for speed performance.[110,111]

In weaving and knitting, rationalization is the word of the day, as with other segments of the industry. The focus is on equipment refinements[112] for small lot flexibility, on productivity, and on automation. Unmanned ring spinning and weaving are already realities.[113]

Textile machinery manufacturers are at the forefront of the art with their rapier, water-jet, and air-jet looms,[114] but find themselves under pressure from foreign competitors because of the yen revaluation. Exports are dropping precipitously.[115]

3.2.2. Finishing

Finishing is another key element in the Japanese textile industry's rise to leadership. The know-how, flexibility, and care finishers placed in nursing through the gray fabrics coming from weavers and knitters were key to the successful commercialization of specialty products (Part 2, Sec. 2.2).

3.2.2.1. Alkaline Treatment of Polyesters

In the early 1970s, finishers popularized the modification of polyester fiber surfaces by aqueous alkaline solutions. Surface hydrolysis (dissolution) proceeds gradually under this treatment without affecting the molecular weight of the remaining portion of the fiber. The diameter

Ink-jet printing systems are making their entry in textile finishing with the prospect of replacing screen printing, which is slower, labor intensive, and environmentally unattractive.

reduction increases fiber or yarn matrix freedom, imparting a softer hand that first served to diversify tactile aesthetics of women's wear. The effect would later be enhanced by combining the treatment with changes in fiber cross-section geometry to confer more silklike character to hard-twist georgette fabrics. As time went on, additional benefits were discovered. Today, the treatment is practiced across the industry to upgrade a variety of commodity fabrics by improving their (1) hands; (2) hydrophilicity or resistance to stain and static electricity buildup; (3) print paste adhesion by fabric surface roughening; and (4) pilling performance via the attendant decrease in fiber tenacity (Part 2, Sec. 2.1.1). It has proven to be equally, if not more, valuable in the finishing of specialty fabrics, particularly in the generation of microcratered, ultralow-density, microporous, and subdenier products, as well as in the sharpening of free fiber ends to simulate furs.[116–119] The fine-tuning of the technology in all of these cases, covered by several hundred patents, has defined conditions ranging from room temperature to 180°C with steam, and from batch to continuous operation.[120] U.S. and European mills overall have not shown the same enthusiasm, partly because of the cost.

3.2.2.2. Topical Finishes

Progress in the fundamentals of topical finishing over the last two decades has established its commercial viability in nearly every category of specialty products reviewed in this report (Part 2, Sec. 2.2). Finish and fiber embodiments frequently complement each other. The first offers economics and flexibility in view of its applicability to commodity fiber-based substrates, while the second brings durability, the active element being an integral part of the fiber. A range of off-the-shelf recipes are essentially available to meet the diverse mechanical and chemical requirements spelled out by end-use conditions.

Plasma treatment of fabrics, a dry alternative to wet finishing is edging toward commercialization. The properties acquired are akin to those conferred by aqueous alkaline finishing—namely, greater depth of coloration, wettability, and antistatic and oil-release properties. The advantages of a dry and fast process are somewhat offset by the investment and operating cost.[121]

3.2.2.3. Printing

Ink-jet printing systems are making their entry in textile finishing with the prospect of replacing screen printing, which is slower, labor intensive, and environmentally unattractive.[122] A design unit first scans the original pattern electronically. The signal, processed with the help of computer graphics software, is then forwarded to the printing unit, which is capable of handling full-width woven and knitted fabrics.

Conditions have so far been specified for cotton, silk, rayon, and nylon; the polyester embodiment is still under development. In addition to being screenless and requiring very little print paste, the process has the extensive coloration flexibility of today's computers and a line accuracy of less than 1 mm. Delivery time from original design to finished fabrics is down to two weeks versus the two months generally taken for screen printing. This development illustrates the type of productivity advances needed by the textile industry to improve its competitiveness (Part 3, Sec. 3.3).

3.2.2.4. Sponging

Menswear fabrics, especially those containing natural fibers, must be dimensionally stabilized prior to cutting because of repeated exposures to steam during sewing and garment assembly. The stabilization process (sponging) involves exposure to heat and water under conditions that vary with each bolt of cloth. Specification of these conditions used to be based on experience (and intuition). Today, a rigorous analytical approach has replaced the guesswork.[123]

More than a third of the manufacturers serving the high-quality segment of the market now share a common sponging facility that stabilizes fabrics for 1.5 million suits annually. All incoming bolts of fabric undergo KES characterization, water absorption determination, and repeated testing for shrinkage and recovery that simulates a number of steam pressing cycles. The results dictate the selection of one of four procedures. Once the treatment is completed, the various tests are repeated to ensure that the goals are met. Last year, the entire procedure was fully automated, thus eliminating all possibilities of erroneous judgment calls.

3.3. Apparel

3.3.1. Automated Sewing

Complete automation of the tailored apparel manufacturing system is Japan's fourth major technological accomplishment. Most of the work toward this goal was conducted during a nine-year MITI project initiated in 1982. A consortium of twenty-eight enterprises from all segments of the industry cooperated in the project. The seed for the initiative lay in the uncertain future faced by a labor-intensive, low-tech industry in a high-wage economy and in the potential for a domestic production capability that had low labor requirements and was flexible, just in time, and quality oriented. The undertaking was ambitious—it called for having a bolt of cloth at one end and tailored garments ready for shipment at the other, without the intervention of human hands in between. It anticipated that manufacturing time would be cut in half. Technically, *The industry envisioned an automated system that would produce jackets, slacks, skirts, dresses, sportswear, and sleepwear.*

the challenge was to apply robotics to the manufacture of sophisticated sewn articles using diverse flexible materials. By the time the project concluded in 1990, essentially all process elements had been demonstrated in the production of tailored women's jackets of woven and knit cloths, patterned and dyed in solid colors. Commercialization of an entire production line, however, was and remains unlikely because of the investment required, which is even greater now that apparel companies are moving their manufacturing bases offshore. Instead, pieces of such a line, optimized for making specific garments or garment parts, are likely to find their way into the domestic industry.[124]

3.3.1.1. The Modules

The industry envisioned an automated system that would produce jackets, slacks, skirts, dresses, sportswear, and sleepwear. The various operations outlined in figures 26 through 29 were conducted at the Tsukuba demonstration semiworks facility for a few weeks at the end of the project.[125–127] A discussion of their main features follows.

3.3.1.1.1. Fabric Inspection

A unit first inspects the fabrics to identify width and length variations, contamination, location and type of defects, pattern or print errors, wrinkles, and color or shading variations. Each inspection system having its own computer can serve as a completely independent unit, though here they are all networked into a system management and control computer. The mechanical and sensing techniques used are conventional, relying on video cameras and image processing to generate the measurements, which are then screened automatically against developed standards to determine fabric acceptance or rejection. Specifically, the line configuration conducts the inspection at 50 m per minute; controls the fabric width within 3 mm and length within 0.3 percent, and rejects soil spots greater than 2 mm^2, holes greater than 1 mm^2, and slubs more than 1 mm thick and 5 mm long. The locations of defects on the accepted fabrics are registered on a defect map transferred to the marker-making and cutting systems for defect avoidance control.

In addition to satisfying the size deviation and defect requirements, the fabrics need to be stabilized to prevent distortion during handling, positioning, and sewing, while avoiding permanent alterations of their hand, appearance, and performance. The stabilization involves backside coating with a resin material. It limits the dimensional, stripe, and texture distortion of woolen fabrics and lightweight knits to 2 percent and raises the minimum bending rigidity above 50 mg$\cdot$$cm^2$/cm (Part 2, Sec. 1.1.1).

3.3.1.1.2. Cutting

A set of sixty-three new rules constitutes the core of a new high-performance pattern-cutting method that has reduced handling time, length of cutting, length of sewing seam, number of operations, and difficulty of pressing. The manner in which two patterns are joined determines, for example, whether the computer can convert them into a single one with related slits, notches, and darts as required. The fabrication of women's blazers was accordingly completely overhauled by combining the front, side, and back panels into only two, and the two sleeve patterns into one; and by modifying the collar and lapel patterns. All told, these various steps reduced total manufacturing time by 20 percent and the number of parts from seventeen to thirteen without affecting garment appearance and comfort.

Two new technologies now permit fully automatic cutting. The first one conceived for single plies is laser based and combined with automatic spreading. Its uniqueness resides in a stationary laser beam reflected to the fabric plane by a swiveling mirror. A lens keeps the beam focused as it moves over a cutting area of 180 cm x 150 cm. Cutting accuracy is within a millimeter, and cutting speed increases by 30 percent. The beam speed (72 m per min) drops to about one-third in corners and notches, while the power is correspondingly adjusted to prevent burning the fabrics. The entire unit is enclosed to ensure ozone removal. Each of the cut parts receives a five-digit identification number applied by an ink-jet printer. The number is read in ultraviolet light as the parts move through the sewing process.

The second technology aims to cut multiple layers of small parts and difficult fabrics with a matrix of 680 vertical blades nested at a density of either four or eight blades per an area of 3 cm x 3 cm. As a fabric stack slowly moves under the cutting assembly, the computer selects the blades needed to form staircase lines that best approximate the pattern shapes. Each of these blades is extended by its own solenoid and mechanically locked in that position for the cutting stroke of the entire matrix. The selection, extension, and cutting steps together take 0.1 seconds. The blades, which have a life expectancy of 500,000 cuts, can handle a stack of compressed plies up to 5 mm thick. With both cutting technologies, the defect avoidance control system takes care of repositioning the garment patterns so as to skip the defective areas.

3.3.1.1.3. Presewing Part Preparation

Most of the cut parts must be prepared for assembly. Those that are to overlap, for example, must be held together temporarily, which is accomplished by using water jets to entangle yarns from superposed plies.

Where an interlining is indicated, a laser system first generates an electrostatic image on the back of the fabric to pattern the deposition of a powdered polyamide adhesive coated with nickel. After a vision system has guided the superposing of the interlining over the fabric, the assembly is bonded by the combined action of squeeze rollers and radio-frequency heating. With the heat confined to the adhesive, the features of the fabric face remain unaffected. Deposition of the adhesive might sometimes suffice to provide the required level of stiffening. Removed from the induction heating zone, the fused parts are picked up by a flexible unit, transferred, and positioned with the assistance of a vision system. They are now ready for sewing.

3.3.1.1.4. Two-Dimensional Sewing

A bobbin thread-feeding mechanism attached to a standard sewing head supplies specific amounts of thread to the bobbin case. Seam dimensions control the length and frequency of feedings. Excess safety thread is removed before each reloading. A sewing head is also available to completely thread a needle, change it, and, if need be, replace the bobbin.

Two vision-controlled systems match patterns. One places a pocket on a front panel and aligns the patterns. The other, attached to a lockstitch and overedge machine, automatically aligns the horizontal stripes of both pieces as they enter the sewing head.

A specifically designed station folds the parts and moves them to a sewing unit for dart seaming. A second machine joins the left and right backs after side seaming, relying on a sophisticated positioning cell and fabric-feed controller. A third one visually recognizes the front and back body parts carried by different conveyors, joins them in the required sewing position, then closes the sides. An edge control guides the parts to maintain an even stitch margin. A fourth one sews a waistband to a skirt as it rotates on a cylindrical clamping support.

The final process is especially noteworthy. A multifunctional system, which consists of a lockstitch and overedge machine and an ultrasonic bonding unit, sews various parts by exchanging processing heads and parts-holding jigs. In the making of jackets, it performs five operations on a jacket body: stitching around the sleeve hole to stop elongation, sewing up the shoulder seam margin, adding side piping, folding the lapel, and taping the shoulders.

3.3.1.1.5. Three-Dimensional Sewing

Mounting shoulder pads and sleeves requires that the parts be static and the sewing head mobile. The jacket body and both sleeves are first placed on a support mechanism that changes size according to garment dimensions. Then a compact, lightweight lockstitch head, mounted on a six-axis robot, performs the attachment by being three-dimensionally driven around the sleeve opening.

3.3.1.1.6. Inspection

Two cameras inspect the dimensions of the sewn parts, one verifying the overall shape, the other the accuracy of their various areas. The quality of seams or degree of puckering is assessed by a laser beam tracing the sewn part surfaces, then plotting out the seam contours (Part 2, Sec. 1.1.5).

Two cameras inspect the dimensions of the sewn parts, one verifying the overall shape, the other the accuracy of their various areas.

3.3.1.1.7. Pressing

The straight seams of sewn parts are held in a straight line by suction as an ultrasonic head opens and flattens them. A separate platen then presses them using heat, steam, and pressure.

The finished garments are three-dimensionally pressed with a flexible dummy, a press system, and a sleeve press. The adjustable panels of the flexible dummy cope with the various shapes and sizes, since each of the thirty-eight panels can move circumferentially and outwardly. The press system consists of a double air bag, the outer one being permeable and allowing transmission of steam and heat to the garment, while the inner one is nonpermeable and provides the required pressure and compliance.

By the time the MITI project ended, it had broken ground in several areas, warranting more than 200 patent actions.[128–131] The following advances deserve special mention:

1. Fabric inspection that produced defect maps to guide subsequent spreading and cutting.

2. Sensing, or the ability to feel and pick up a single fabric ply much as the human hand does (figs. 30, 31).

3. Temporary stabilization of a fabric via selective resin application to its backside to facilitate manufacturing.

4. Discrete interlining (face-fabric bonding via induction heating of a nickel-coated polyamide adhesive.

5. Vision-controlled two-handed robotics.

6. Stripe and plaid alignment for part sewing.

7. Three-dimensional sewing with light, low-inertia, mobile heads mounted on multiaxis robot arms.

8. Final pressing on inflatable forms adjusted for garment shape and size.

Furthermore, hardware and software were formulated to handle fabrics that exhibit a range of KES mechanical properties (Part 2, Sec. 1.1.1), regardless of their constructions and yarn compositions.

3.3.2. Just in Time

The MITI project embodies an extreme trend in apparel production technology by relying exclusively on automation. But over the past twenty years, the industry has developed a variety of efficient labor-intensive approaches that have shortened delivery time, offered greater styling flexibility, and improved product quality. These approaches have also helped trim the workforce and warehousing needs, thus lowering cost.[132–134]

The manufacturer initiated a comprehensive overhaul of one of his plants with a ten-year goal of cutting one day every two years in order to eventually deliver a suit within a single day.

Ergonomic analyses of garment making inspired most of these novel approaches. For example, in the mid-1970s, a menswear manufacturer that retails part of its production established that its customers had to wait six days on average to pick up made-to-order suits, even though fabrication took only three and a half hours. Idle time between steps accounted for the delay. The manufacturer initiated a comprehensive overhaul of one of his plants with a ten-year goal of cutting one day every two years in order to eventually deliver a suit within a single day. Floor layout, material conveyance, technical competence, emphasis on quality and versatility, sensitization to cooperation and overall efficiency, and proven operation automation were among the many areas addressed.[135] Though not anticipated, the gains in flexibility and just-in-time delivery now help the industry fight imports by offering made-to-order suits for a minimal premium.

As a technical sideline, that same plant initiates fabrication only if the KES parameters of the incoming fabrics fall within specified ranges. These values are given color codes on the data sheet that guides sewing operators. The closer the colors are to those of the optimum specifications, the less care the operators must apply in controlling over- and underfeeding. The rationale is that such fabrics are sufficiently forgiving—that is, possess enough extensibility, resilience, and so on—to compensate for some departures from the optimum sewing conditions and still yield seams with puckering levels within norms. Interestingly, the ranges of acceptable KES parameters were formulated prior to the MITI project and labelled "pre-automation" specifications, indicating the tolerance that should be programmed into an automated sewing process.

3.4. Notes

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(2) Studies of the Drapability of Sewn Fabrics

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- "Dependence of Various Sewing Conditions on the Bending Property of Seam."
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(3) Development of a New Pattern-Making System

- "Generation of the Structured Data for the Analysis of Three-Dimensional Shapes of Garments."
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SUMMARY

At this point, it seems appropriate to stand back and place in perspective the key technical advances just reviewed. Five of them stand out as representative of the art.

The emergence of predictive capabilities heralds a fundamental science of textile engineering.

The first involves the method that allows the objective specification of fabric and apparel quality. The emergence of predictive capabilities heralds a fundamental science of textile engineering (Part 2, Sec. 1.1).

The second relates to the array of specialty products, particularly those based on yarns containing two or more polymers and their ultrafine-filament derivatives, which have no natural counterparts (Part 2, Sec. 2.2). They usher in a second age for synthetics, confounding the many who considered the field not susceptible to renewal.

The third is the expertise and care consistently shown by fabric finishers in developing yarn potentials (Part 2, Sec. 3.2.2). Both are central to the success of the specialty products* now recognized worldwide as a hallmark of the Japanese industry.

The fourth is the demonstrated feasibility of all the elements needed to completely automate the manufacture of tailored garments. This first application of robotics to flexible materials introduces several revolutionary fabrication concepts (Part 2, Sec. 3.3.1).

The fifth is the steady increase of processing speed and automation throughout spinning, weaving, printing, and apparel making (Part 2, Sec. 3). Programming such operations demands complete process definitions based on product fundamentals.

Japan's leadership in the first four of these areas is at the moment unchallenged. In the fifth one, Japanese textile mills have to reckon with offerings from European textile equipment manufacturers, which in

* Two recent publications (see Part 2, notes 84 and 135) might help readers who are broadly interested in current market offerings. This report is limited to illustrative cases.

certain instances are as technologically advanced and cost-competitive as domestically produced counterparts.

For its part, the U.S. apparel industry chose to travel a different course. Its strategy is driven mainly by cost, with yield, speed, and product uniformity at the top of its agenda and new process development drastically reduced. Having gradually lost its equipment manufacturing segment, it relies on developments from foreign manufacturers for process modernization. The attention given to quality bears primarily on uniformity and processibility. Introduction of product variants is kept to a minimum and frequently prompted by pressure from imports in the lower half of the market. The mills have not been challenged by the specialty products covered in this report. These products are practically unavailable here because the currency exchange rate makes them exorbitantly expensive. The situation would likely change, though, were their prices to drop as a result of off-shore manufacturing. Development of specialty products based on novel concepts has also been curtailed on the assumption that the U.S. consumer would not support the premium. The industry clearly continues to aim at a volume business and shows reluctance to diversify. Further evidence of this reluctance is found in the industry's phaseout of mid- and long-range research and in the focus of its limited technical resources on existing businesses. Both steps emphasize the overriding importance of short-term payoff.

Japanese and American strategies thus differ, and the contrast has grown over the years. Indeed, several developments presented in this report originated in the United States. But, as time went on, the industry here became complacent, while the Japanese latched onto the trends and improved on them. Time will tell which of the two will prevail in the barrier-free, fiercely cost- and quality-competitive world envisioned by WTO.

PART 3

The Future

The Japanese textile industry complex has by all accounts tallied an impressive technical record over the past three decades. But the thrust of its future R&D efforts is no longer clear. This section addresses that uncertainty and offers a possible scenario.

3.1. Predicament of the Japanese Industrial Establishment

High labor costs and sharp appreciation of the yen are hurting Japanese exports. In response, the industry is moving its manufacturing base offshore so as to continue serving the world's markets. Imports to Japan are concurrently experiencing an explosive growth in some sectors. To prevent the loss of its domestic market share in those cases, Japan even imports some of its own overseas production. This trend is expected to increase in the foreseeable future.

Competitive advantage, thus leadership, in the developed world no longer depends on financial control and traditional cost advantages but on brain power—technology, marketing, and management acumen.

The projection made by Peter Drucker in the early 1990s is rapidly coming to pass: leading Japanese companies are reacting to the market's economics by adopting new business strategies[1] that rest on two tenets. The first is that blue-collar manufacturing in Japan is a misallocation of resources that weakens both the companies and the national economy—hence Japan's large investment in many parts of the world. Officially, though, companies invoke foreign protectionism (real or imagined) and domestic labor shortages to justify their moves. The second is that competitive advantage, thus leadership, in the developed world no longer depends on financial control and traditional cost advantages but on brain power—technology, marketing, and management acumen. Companies therefore plan increasingly for the systematic abandonment within a set period of time of their own products and for the replacement of total quality management with zero-defect management. In essence, the strategies call for manufacturing to occur abroad at sites dictated by economics[2] and for R&D to be conducted at home. With knowledge at a premium, no resources are spared. Time is of the essence, thanks to cross-functional lines, introduction of new products takes half as long as in the United States.

The downside of this perspective is the impact of production cuts on Japanese workers and the attendant need to provide them with new jobs.

No sector is experiencing a greater upheaval in manufacturing than textiles.

3.2. Situation of the Textile Industry Complex

No sector is experiencing a greater upheaval in manufacturing than textiles. Imports already meet more than half of consumers' needs (see Part 1). Many jobs have already been lost in the rationalization of the industry. Hundreds of thousands more are at risk because of the anticipated continued growth of offshore operations. The WTO-mandated abolition of quotas restricting textile and clothing trade within the next ten years will create competitive pressures on many national textile industries, including Japan's, which might be downsized further. The inability of offshore facilities to match the quality of some domestic production and the spread of automation throughout the industry mitigate these pessimistic prospects and secure, for the time being, the survival of a fraction of the industry. Were the first of the two factors mentioned earlier to disappear, the situation would be grim indeed.

However, the global future of Japanese-controlled textile mills overseas is bright, barring unforeseen political developments. Products of steadily improving quality easily hold their own against incumbents at competitive prices. As manufacturing sophistication grows, these mills will likely produce specialties now produced in Japan (Part 2, Sec. 2.2). These products will constitute a technical and business challenge for U.S. and European manufacturers, but will find tough competition from knockoffs already starting to come out of other Asian countries.

On the R&D side, the industry probably has little new textile knowledge to glean from abroad because of its strong technical leadership. Only in the area of equipment is there more to learn, since four of the six largest manufacturers in the world are European.

3.3. Research and Development

The present conjuncture has had little impact on research funding of the overall industrial establishment and its long-range strategy (Part 1, Sec. 1.3). The emphasis is shifting, though, from applied to basic research, which reflects the premium placed on knowledge (Part 3, Sec. 3.1). It also moves away from investigating a single technology or material to exploring multicomponent technologies. Thus, interest in horizontal integration,[3] or technology fusion, as Fumio Kodama calls it,[4] is growing.

When it comes to the textile sector, changes in specific objectives are unavoidable to meet the imperatives of accelerating globalization (Part 1, Sec. 1.4). Innovation in manufacturing is likely to receive more attention than innovation in products in cases where Japan already commands a substantial lead over its closest competitors.

3.3.1. Manufacturing

Lowering cost to combat imports should drive programs aimed at quality, productivity, and flexibility. Continuous in-line monitoring coupled with advanced signal analysis techniques (fuzzy logic) should gradually replace off-line testing to provide better process insights and thus better yields and product quality. Similar benefits should be reaped from gains in fiber and yarn mechanical fundamentals that improve predictive capabilities of fabric and apparel properties. Efforts to automate and to raise processing speed should continue to reduce labor content with the help of a state-of-the-art textile equipment manufacturing industry. While productivity (output per machine-hour) in yarn manufacturing and fabric formation rose severalfold over the last two decades, the speed of finishing improved only moderately and is certain to draw attention. Advances can therefore be expected in dyeing, printing, heat transfer, chemical application and recovery techniques, and fabric stabilization. Improved manual garment assembly and progressive automation will provide the flexibility needed for small-lot and even one-of-a-kind production. With the trend toward made-to-order garments, walk-in booths (fig. 32) for automatic body measurement at the retail point may reach commercialization to ensure consistent garment fit.[5] Finally, society's greater sensitivity to ecological issues will force industry to dedicate a larger part of its resources to the development of more environmentally acceptable technologies.

In time, Japanese-controlled textile mills overseas will benefit from some of these advances and will thereby strengthen their worldwide competitiveness.

3.3.2. Products

Over the years, Japanese researchers have managed to introduce a steady flow of specialty textiles (Part 2, Sec. 2.2). Today, they appear close to running out of steam. Even in the field of subdeniers, with its potentially unlimited number of product-feature combinations, innovation has become rare (Part 2, Sec. 2.2.7.1) and the consumer blasé. Economics matter more than ever and foreign competition continues to intensify, making novel aesthetics increasingly difficult to come by. The development of novel aesthetics, which drew significant resources in the 1980s, can be expected to move down the research priority list. At this point, the industry would probably like to maximize profits without further investment. Across-the-board reductions of textile research staff—by as much as two-thirds in the past five years at one major fiber producer—are indicative of the trend. Consideration may also be given to practicing some of these technologies at skilled offshore plants, which would open the door to world markets. Personnel affected by this curtailment are reassigned to support the development of optical, hollow, semipermeable, and carbon fibers for semitextile and industrial products manufactured by electronic, medical, environmental, and advanced material businesses.

However, in addition to a minor effort toward biodegradable fabrics, two new areas of investigation show promise for the apparel field.[6,7]

Shape-Memory Polymers

A new class of organic materials, sometimes referred to as "smart" because of their ability to respond significantly and reversibly to environmental changes, are being commercialized with the promise of revolutionizing a great many articles ranging from fibers and textile finishes to moldings. The focus is primarily on a family of polyurethane block copolymers, made of alternating soft and hard segments, which show large changes in their physical and mechanical properties at their glass transition temperatures. The applications envisioned to take advantage of these changes dictate the selection of the transition temperatures (mostly in the 10 to 50=B0C range), thus of the copolymer compositions.[8]

The molecular relaxation occurring when the soft segments get up to the transition temperatures accounts for the property changes. First, increases (2–3x) in gas permeability translate into greater membrane breathability[9] used in sportswear (Part 2, Sec. 2.2.6.4), diaper covers, and footwear. Artificial skins and wrapping films are under development. Second, drastic reductions of modulus (100–200x) allow relatively small forces to reshape articles.[10,11] Cooling them below the transition under the applied forces suffices to freeze them in the new shapes. Third, reheating the newly shaped articles above their transition temperatures without application of any forces restores their original shapes, hence the label of shape-memory. That memory rests on crystallites of the hard segments unaffected by the thermal cycle just described. Artificial hair, linings, and utensils for the handicapped are already commercial. Last, improvement in damping opens the door to the development of blood vessels, underwear including brassieres, insoles, and anti-wrinkle cosmetics.[12]

A new class of apparel finishes combines the second and third of these properties.[13,14] In one instance, finishes with transition temperatures around 40=B0C stiffen shirt collars and cuffs at room temperatures. Wrinkles disappear with an air blast from a hair dryer which briefly raises these parts of the shirt affected above 40=B0C. In a second instance, creases and pleats set near the melting points of finishes having transition temperatures in the vicinity of –10=B0C do not stiffen or wrinkle at room temperature. In a similar vein, claims are made for textile and semitextile products capable of regaining their original shapes after intentional compaction, as in diaper packaging, slackening of form-fitting garments, and futon matting.[15,16]

The voluminous patent literature and number of players indicate the attention given to the field. Recent disclosures have added polyesters to the family of shape-memory materials.

Kansei Engineering

Convergent needs, interests, and technical advances are coalescing into a new discipline aimed at improving human well-being by optimizing physiological and psychological environments. One aspect of this all-encompassing objective is the design of products—including textiles—with an eye on observable physiological responses to the stimuli they engender. The ultimate goal is to tailor products to the preferences of each consumer.[17] The three-step approach being followed seeks to (1) develop techniques that permit the quantitative characterization of physiological responses (e.g., brain signals, electromyographs, hormone releases, and so on); (2) generate statistically significant correlations between such measurements and stimuli magnitudes; and (3) design products that trigger improved consumer responses.[18] Correlations are emerging between preferred sensory perceptions (tactile, visual, auditory), brain-wave patterns, and stimulus dimensions. Fluctuations in the frequencies of these perceptions tend to obey power laws like those characterizing many periodic phenomena in nature.[19,20] Already, a fiber producer is attempting to link visual and tactile preferences for fabrics, and ultimately brain-wave patterns, with fluctuations in the periodicity of their surface irregularities. The outcome of such investigations would be a new class of more “pleasurable” products.

The fundamental and long-range character of this work illustrates the shift toward basic research. Though it has its detractors, the pursuit has enough support to warrant academic involvement,[21] a nine-year government-funded project,[18] and participation from an industry always on the lookout for new turf.

Convergent needs, interests, and technical advances are coalescing into a new discipline aimed at improving human well-being by optimizing physiological and psychological environments.

The aura of advanced technology cast over this industry during the past two decades is unlikely to tarnish anytime soon.

3.4. A Final Note

The negative trade balance in textiles and other attendant problems cast a shadow on the future, which has prompted a drastic downsizing of Japan's domestic production. Various actions seek to secure continued employment for the affected workforce. The technical leadership, however, does not appear threatened. In fact, its impact worldwide will probably increase with the offshore manufacture of products already commercialized in Japan. However, the pace of product innovation in apparel textiles will slow in the near term as more resources are dedicated to longer-range fundamental research. Advances in conventional and smart materials and human sensory perceptions coupled with a one-of-a-kind production capablility could usher in a time when the industry might literally personalize apparel to meet the physiological and psychological comfort requirements of each consumer. Recent progress in that direction seems to ensure that the aura of advanced technology gained by over this industry during the past two decades is unlikely to tarnish anytime soon. This scenario would only be altered if corporate profits—and hence research funding—were impacted by lower profitability of offshore operations due to further deterioration in the rate of exchange.

3.5. Notes

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[4] "Technology Fusion and the New R & D." F. Kodama. Harvard Business Review, July–August 1992, pp. 70–78.

[5] See Part 2, note 131.

[6] "Shimadzu and Kanebo Develop Biodegradable Synthetic Fiber." JTN **480**, November 1994, p. 14.

[7] See Part 2, note 81.

[8] "Properties and Applications of Polyurethane-Series Shape Memory Polymer." S. Hayashi, International Progress in Polyurethane, vol. 6, 1993, pp. 90–115.

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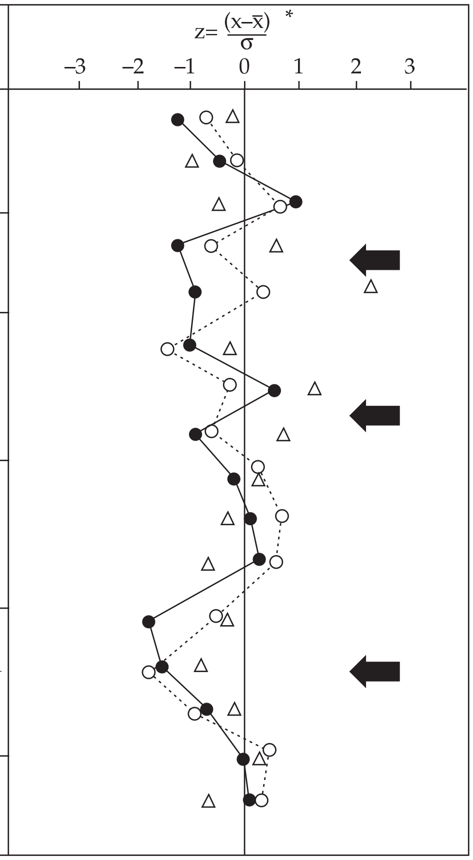
FIGURES

Modes of deformation	Symbols	KES parameters
Tensile	LT	Linearity
	WT	Tensile energy
	RT	Resilience
Bending	B	Bending rigidity
	2HB	Histeresis
Shearing	G	Shear stiffness
	2HG	Histeresis at $\phi = 0.5°$
	2HG5	Histeresis at $\phi = 5°$
Compression	LC	Linearity
	WC	Compressional energy
	RC	Resilience
Surface	MIU	Coefficient of friction
	MMD	Mean deviation of *MIU*
	SMD	Geometrical roughness
Thickness & Weight	T	Thickness at 0.5 gf/cm^2
	W	Weight per unit area



Key: Wool-like Polyester Wovens

● cashmere/wool 40-60 (target)

○ novel polyester candidate (SW-1)

△ polyester incumbent (commodity)

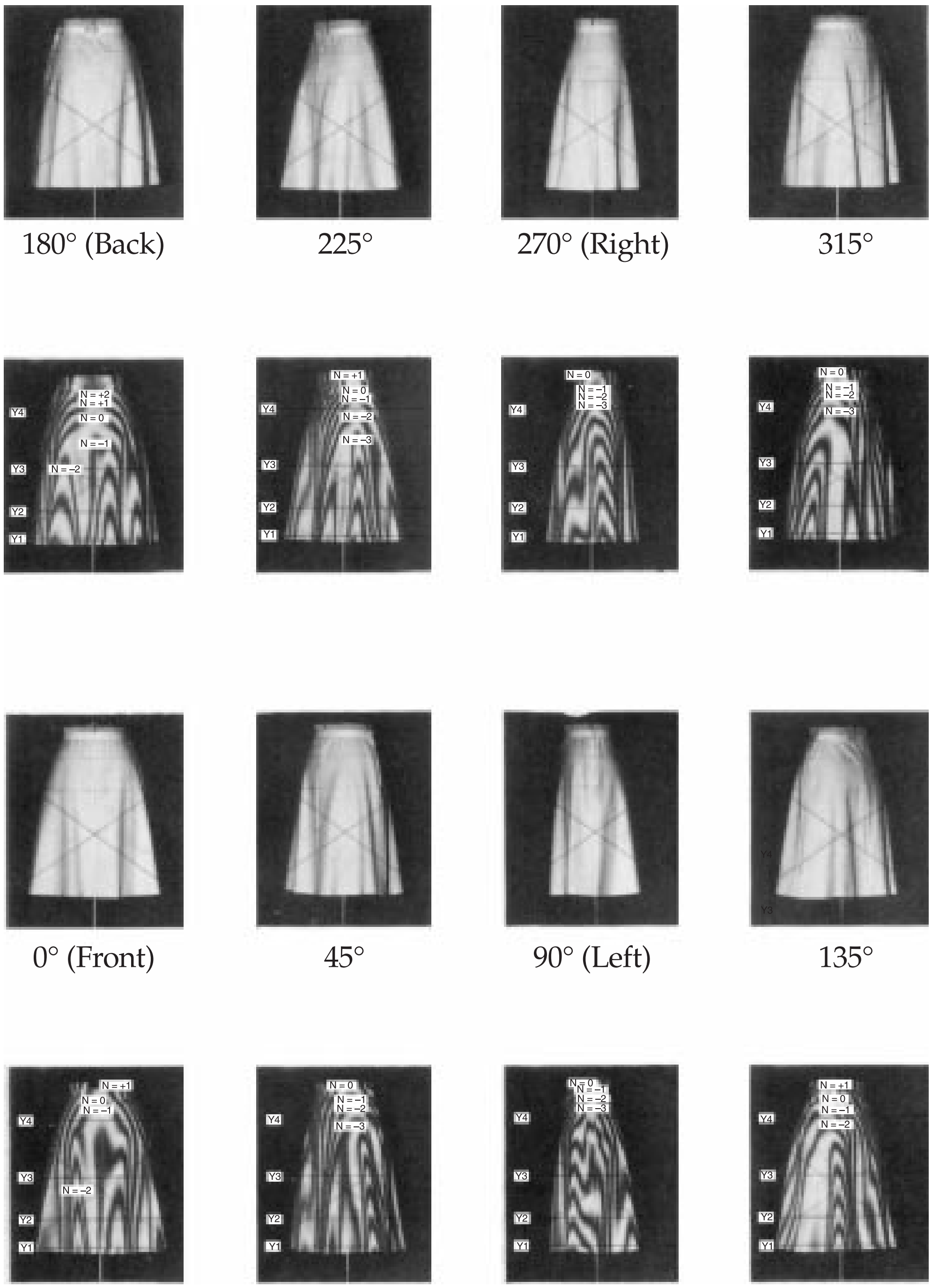
*z = normalized standard deviations from the average values obtained for the 214 fabrics composing the winter suiting reference portfolio.

Conclusions

1. The objective is the complete overlapping of the polyester and wool fabric lines.
2. The arrows mark the areas of largest discrepancy between the commodity and the target.
3. The proximity of the SW-1 and wool lines gives a measure of the technical advance and of what remains to be done to fully meet the objective.

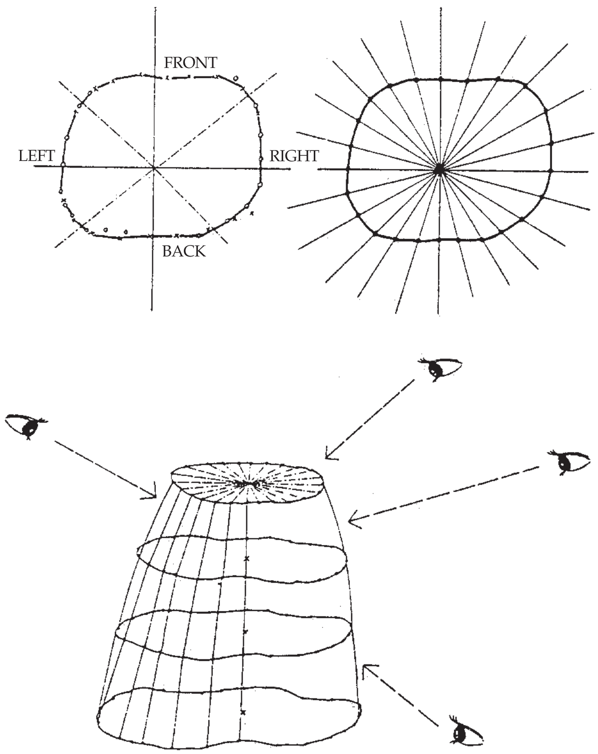
Source Shimada, K. and O. Wada. 1982. "New Development of 100% Polyester Spun Woven Fabrics." Proceedings of the Japan-Australia Joint Symposium on Objective Specification of Fabric Quality, Mechanical Properties, and Performance. Kyoto, Japan, May 10-12.

Figure 1. A comparison of KES fabric profiles (Teijin Co., Ltd.)

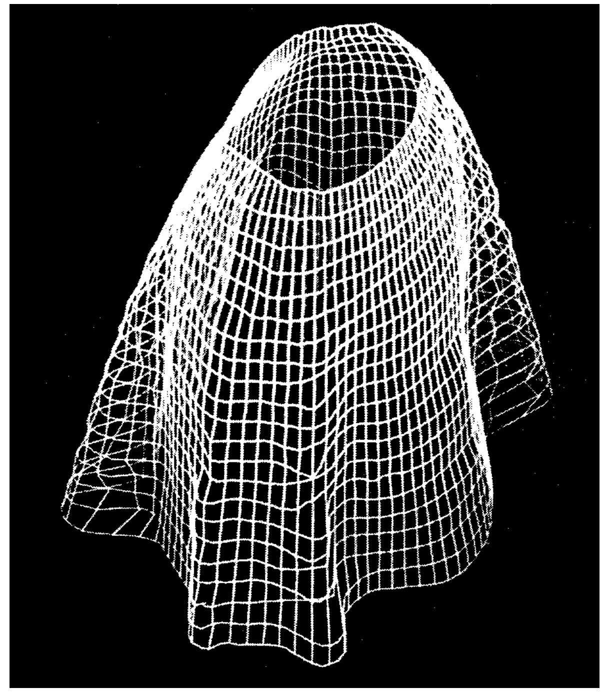


Source Suda, N. et al. 1984. "Studies on Three-Dimensional Shape of Garments." *Bull. Res. Inst. Polym. Text.* 142(9):5-28.

Figure 2. Skirt moiré topography (wool serge S-1)



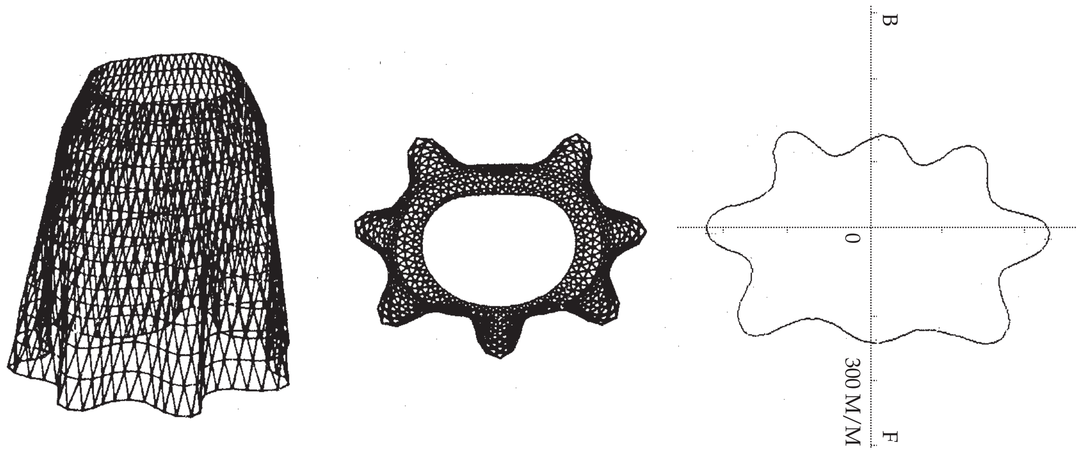
Algorithm



Flared-skirt product

Source Akami, H. et al. 1984. "Development of a New Pattern System." *Bull. Res. Inst. Polym. Text.* 142(9):63-96.

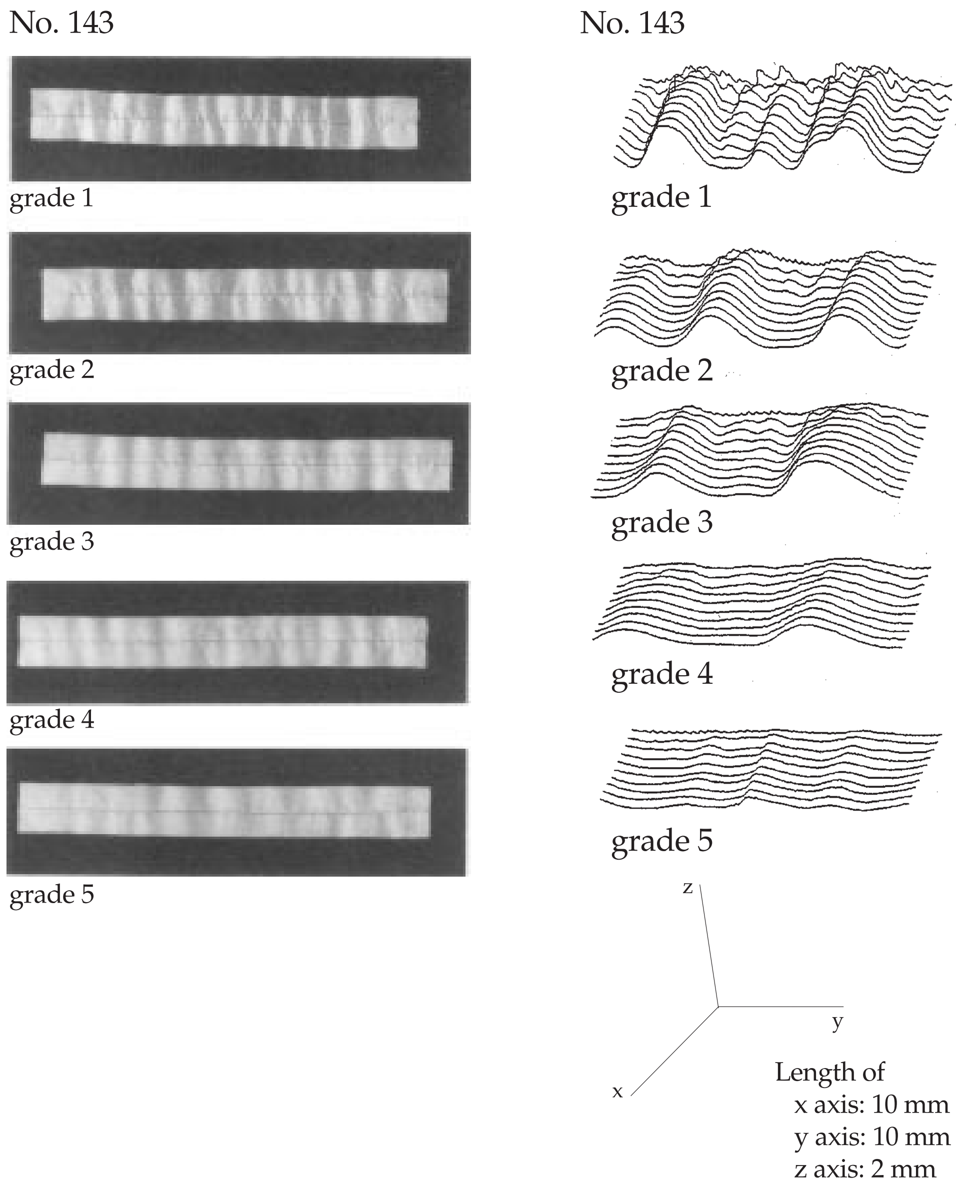
Figure 3. Three-dimensional skirt representation (based on moiré fringes)



Calculated Actual

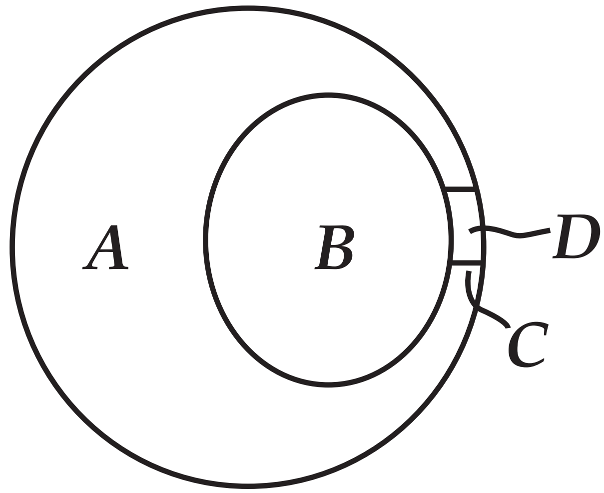
Source Akami, H. et al. 1984. "Development of a New Pattern System." *Bull. Res. Inst. Polym. Text.* 142(9):63-96.

Figure 4. Skirt model – wool serge
(based on triangular finite elements)



Source Inui, S., A. Shibuya, and N. Aisaka. 1992. "Method of Evaluation of Seam Pucker Using Laser Topography." *Bull. Res. Inst. Polym. Text.* 169(3):63-71.

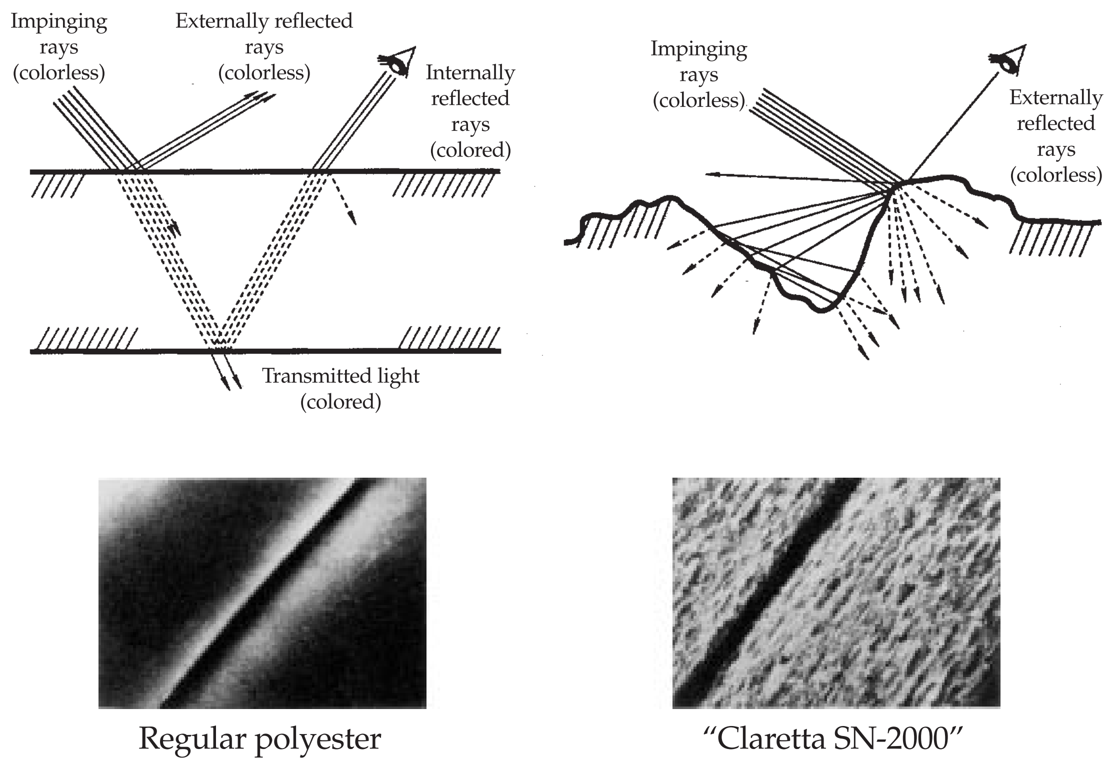
Figure 5. Seam-puckering laser topography



A: Polyamide
B: Polyurethane
C: Sheath (thinnest section)
D: Neck

Source Kanebo, Ltd. 1990.

Figure 6. Conjugate-spun hosiery (Kanebo, Ltd.)



Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

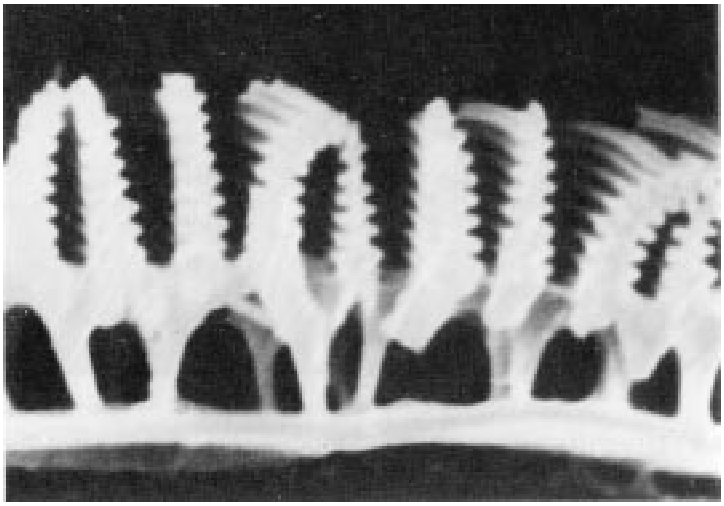
Figure 7. Microcratered fibers (Kuraray Co., Ltd.)

Below 11°C

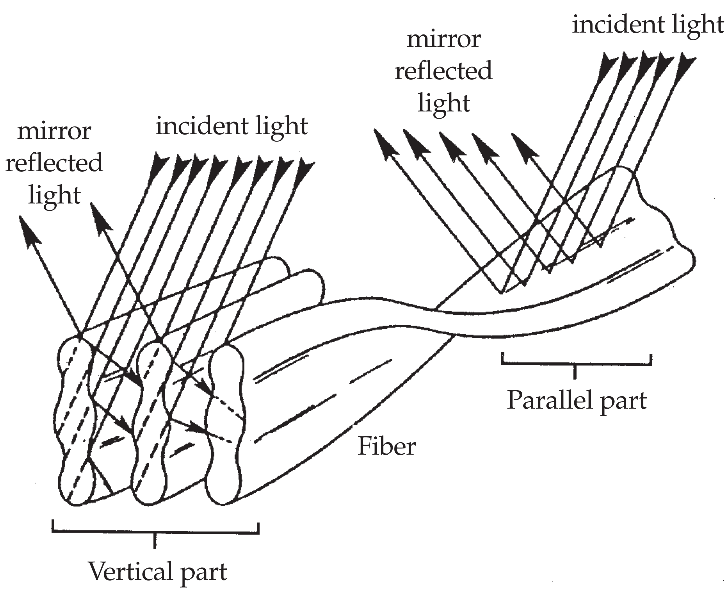
Above 19°C

Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

Figure 8. Thermochromic "sway" skiwear (Toray Industries, Inc.)



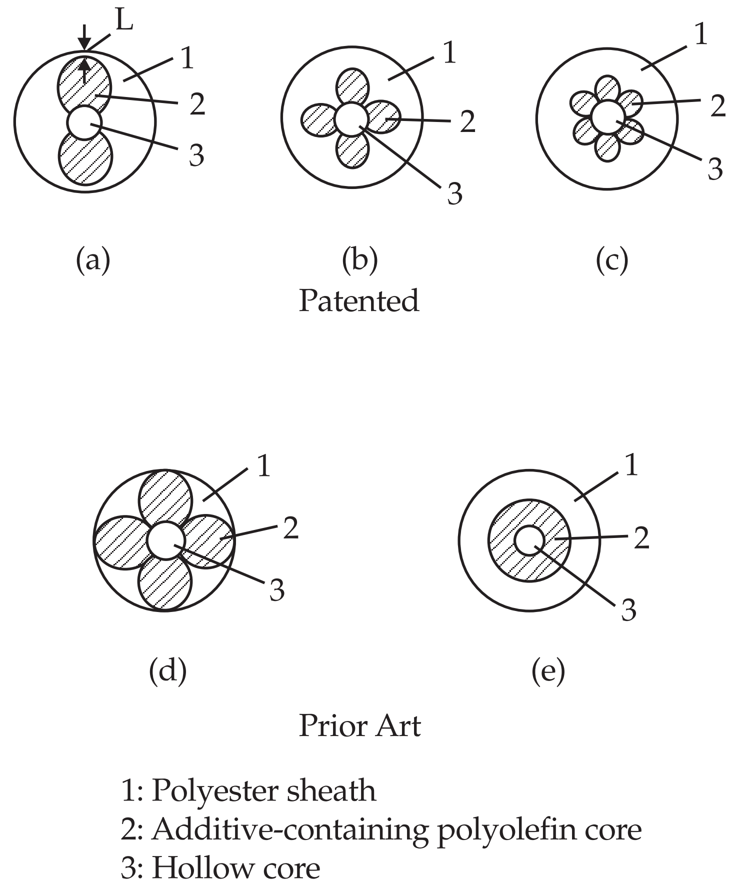
Morpho alae butterfly wing face



"Deforl"

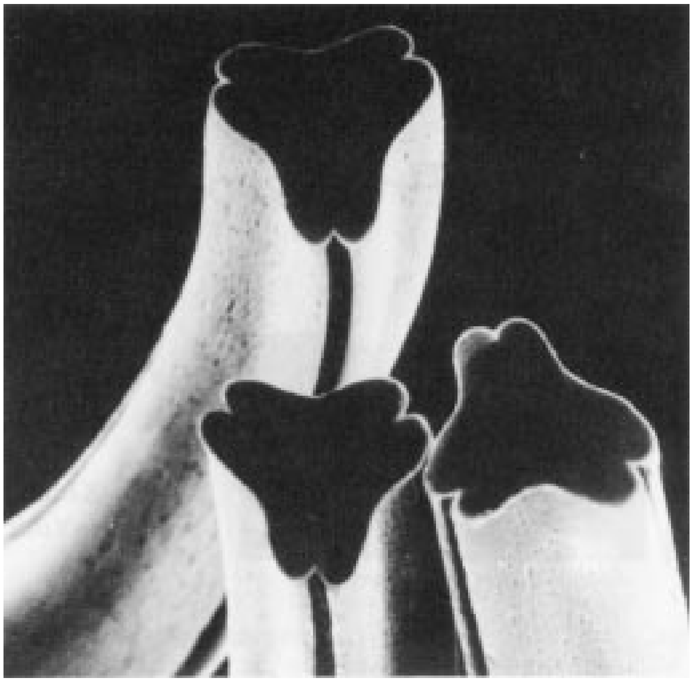
Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

Figure 9. Butterfly wing simulation (Kuraray Co., Ltd.)

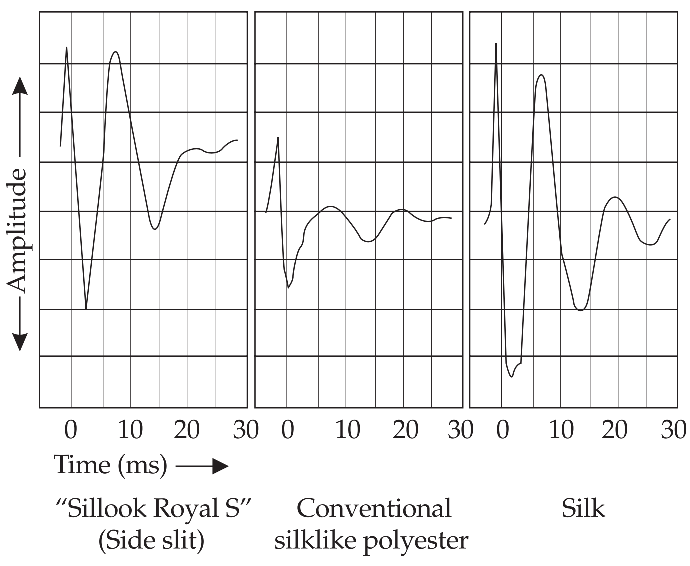


Source Mitsubishi Rayon Co., Ltd. 1987.

Figure 10. Fragrant textiles (Mitsubishi Rayon Co., Ltd.)

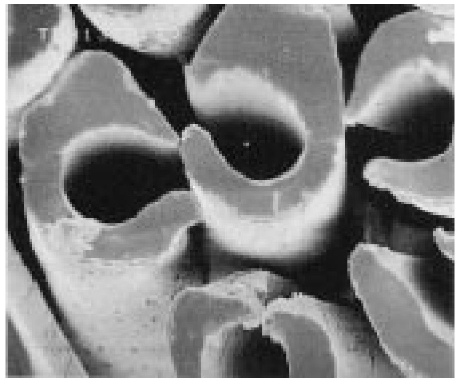


“Sillook Royal S”

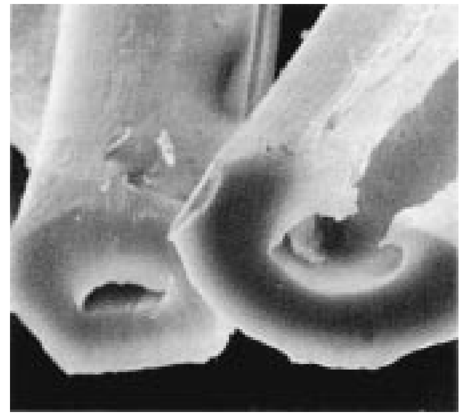


Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

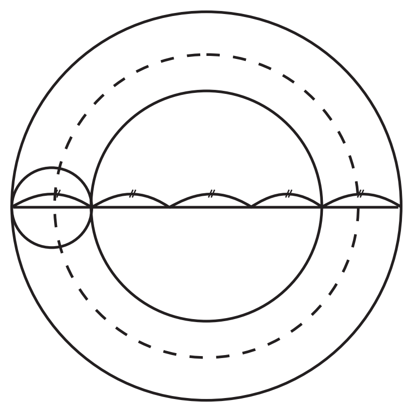
Figure 11. Scrooping polyesters (Toray Industries, Inc.)



"Killat N"
(Kanebo, Ltd.)



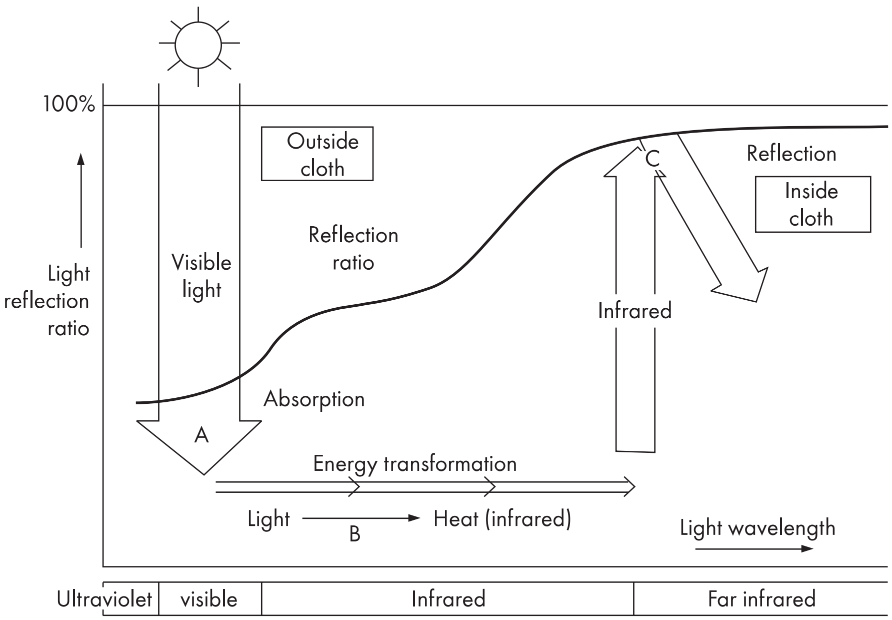
"Aege"
(Mitsubishi Rayon Co., Ltd.)



Model of aerocapsule (Teijin Limited)

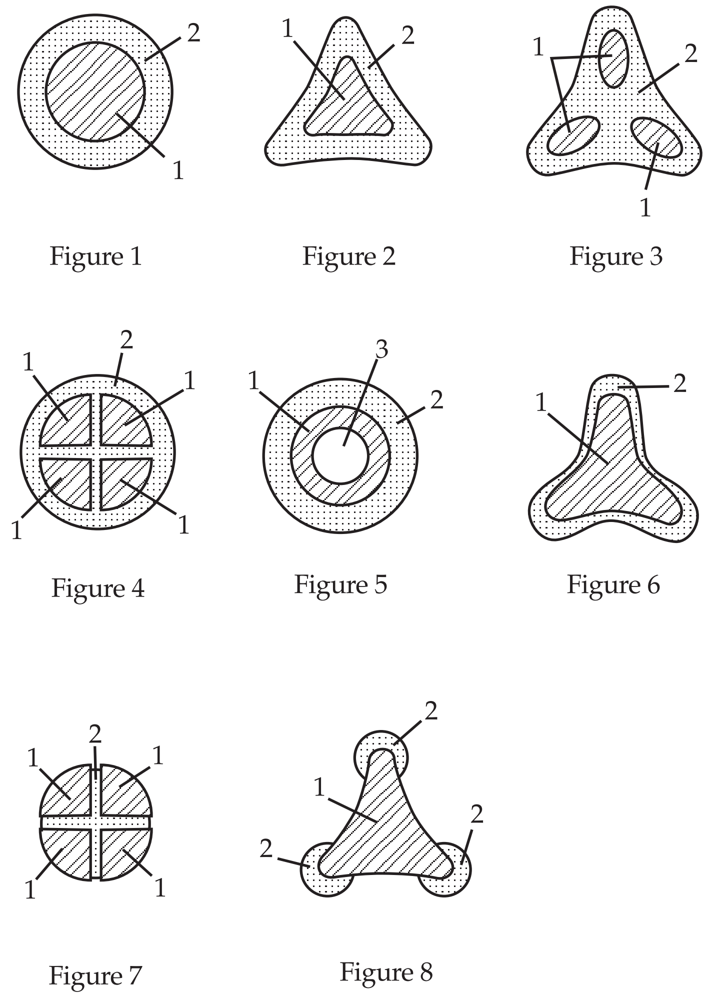
Source "New Hollow Filaments From Kanebo."1992. *JTN, The International Textile Magazine*. 455:45.

Figure 12. Ultralow-density polyesters



Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

Figure 13. Light-to-heat conversion—fabrics ("Solar α," Descente Ltd.)

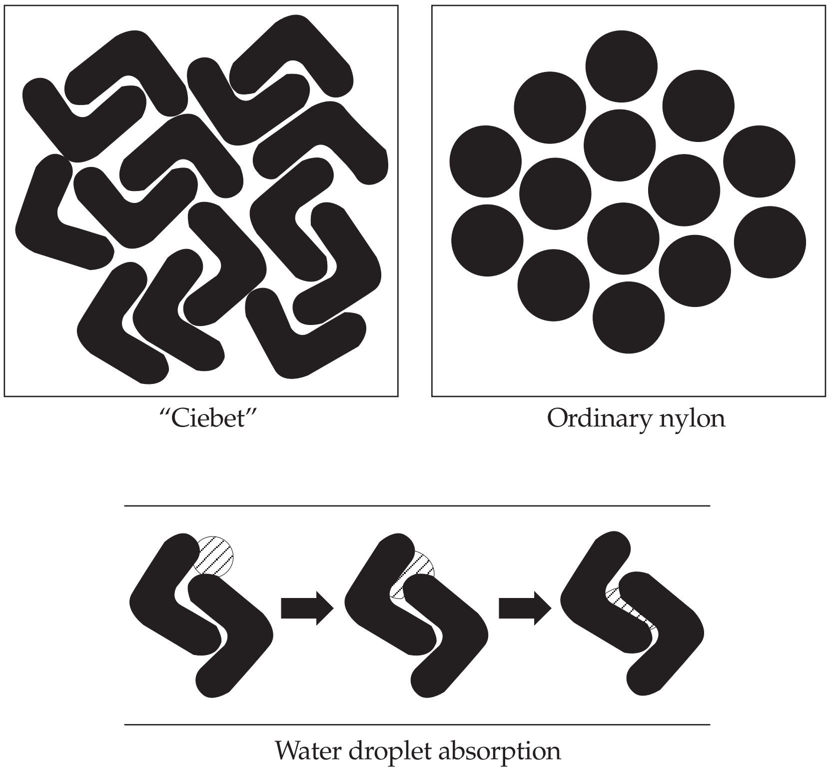


1: Additive-containing core
2: Soluble sheath
3: Hollow core

Figures 1–6: Patented cross sections
Figures 7–8: Fibers of figures 4 and 6 after sheath solubilization

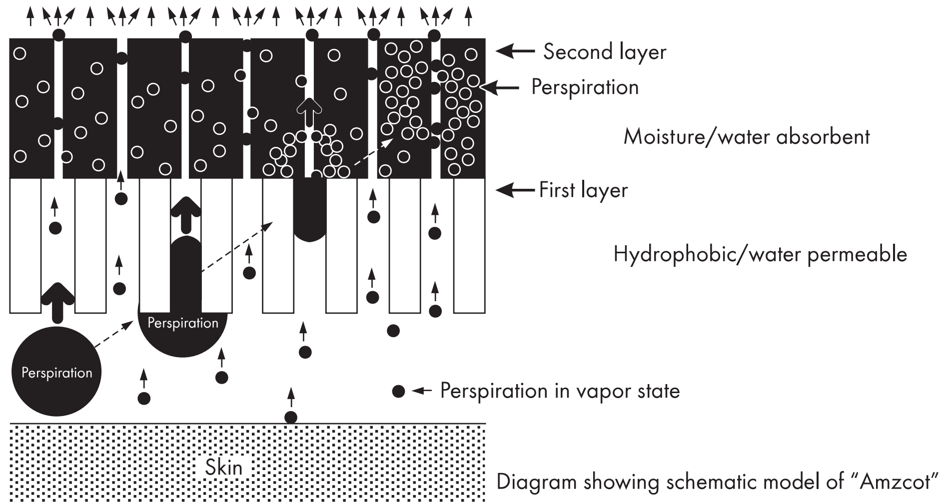
Source Kanebo, Ltd. 1988.

Figure 14. Light-to-heat conversion—fibers (Kanebo, Ltd.)



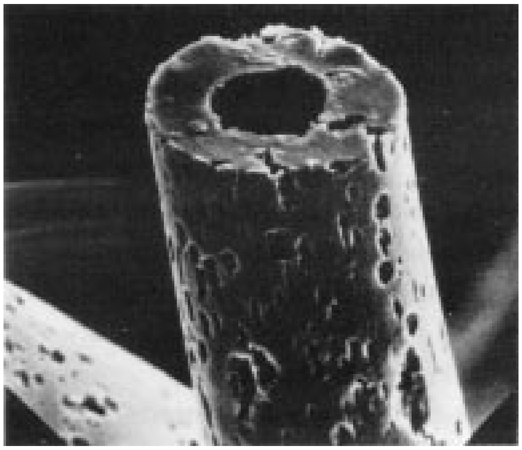
Source "Ciebet—Perspiration Absorbent Nylon." Technical brochure.

Figure 15. L-shaped cross-section nylon fibers
(Asahi Chemical Industry Co., Ltd.)

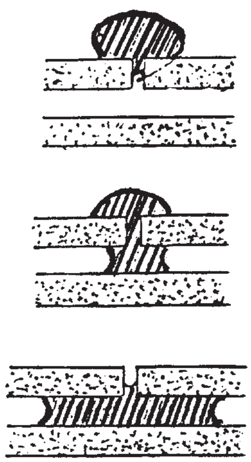


Source Sakashita Co., Ltd.

Figure 16. Double-layered sweat-absorbing fabrics (Sakashita Co., Ltd.)



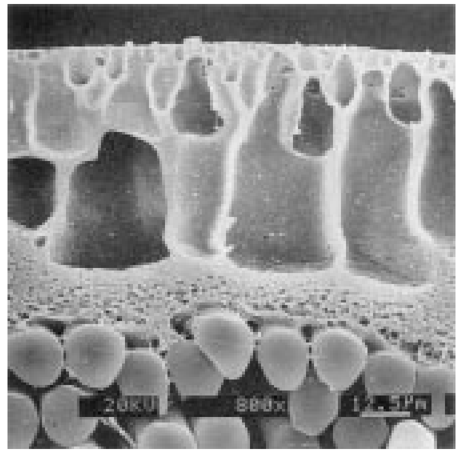
"Wellkey"



Sweat penetration process

Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

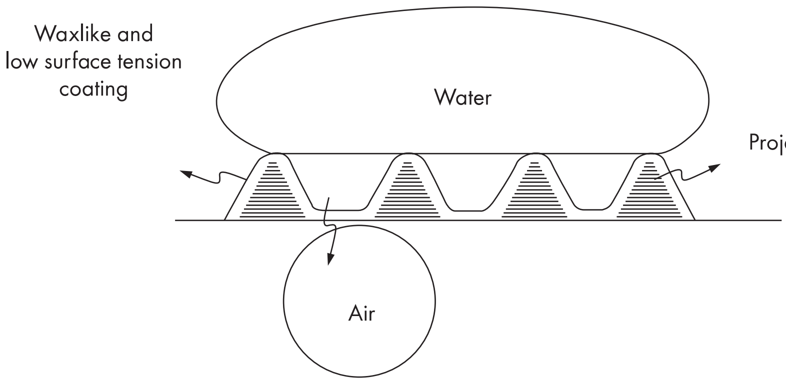
Figure 17. Microporous hollow polyesters (Teijin Co., Ltd.)

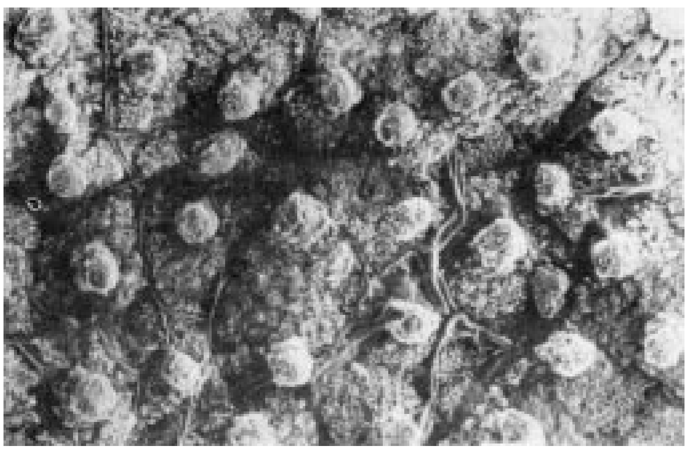


"Entrant GII"

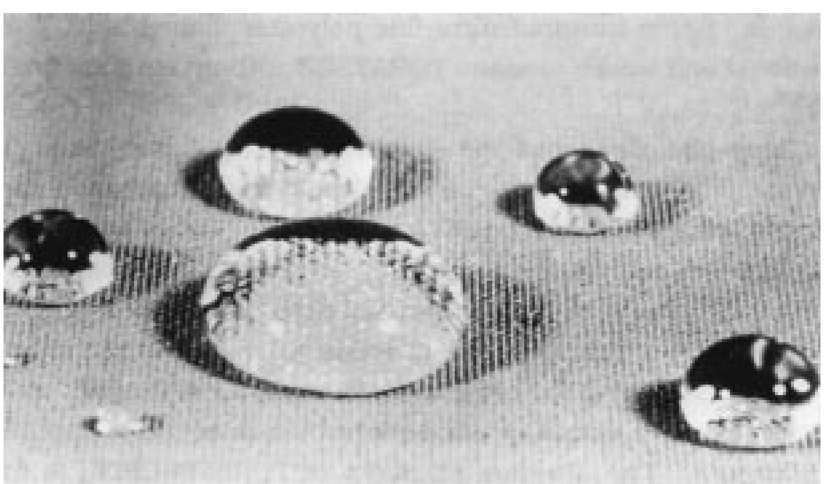
Source "High-Performance Waterproof Breathable Fabric 'Entrant G II'." 1993. *JTN, The International Textile Magazine.* 459:39.

Figure 18. Breathable impermeable outerwear (Toray Industries, Inc.)





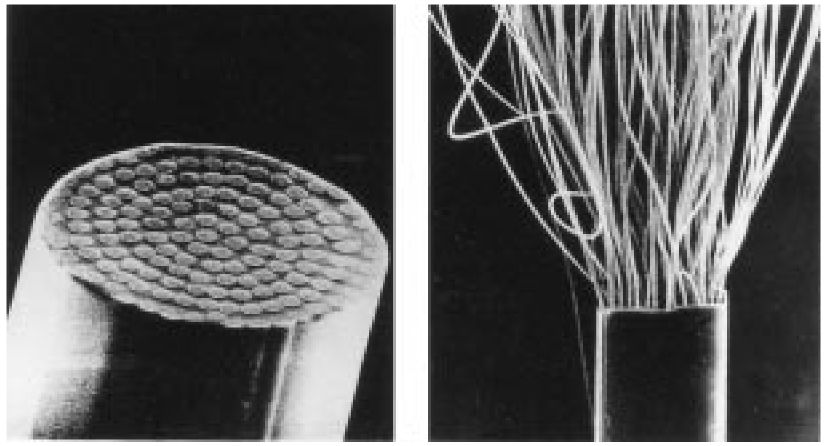
Water droplet in fog/rain (100 µm)
Lotus Leaf



"Super-Microft"

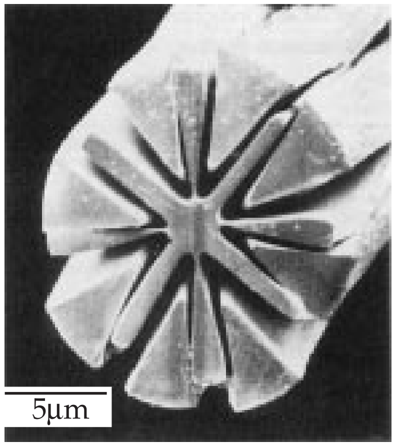
Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

Figure 19. Polyester fabrics based on lotus leaf design (Teijin Co., Ltd.)



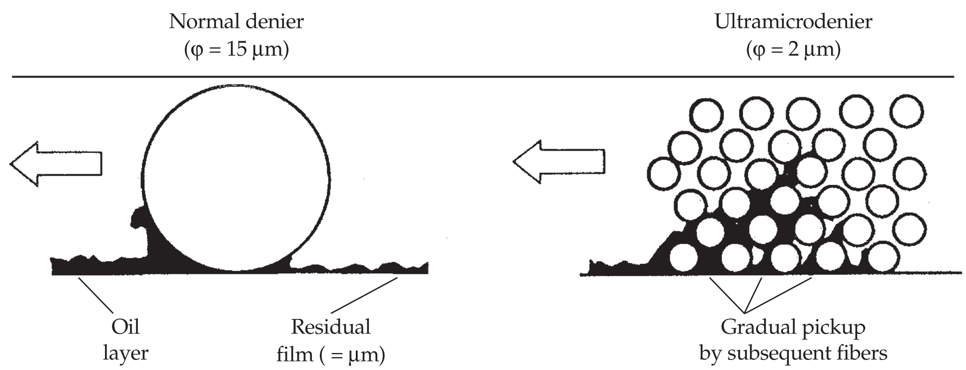
Source "Various Microfibers for Clothing." 1992. *JTN, The International Textile Magazine.* 450:81-83.

Figure 20. "Sea-island" fibers (Toray Industries, Inc.)



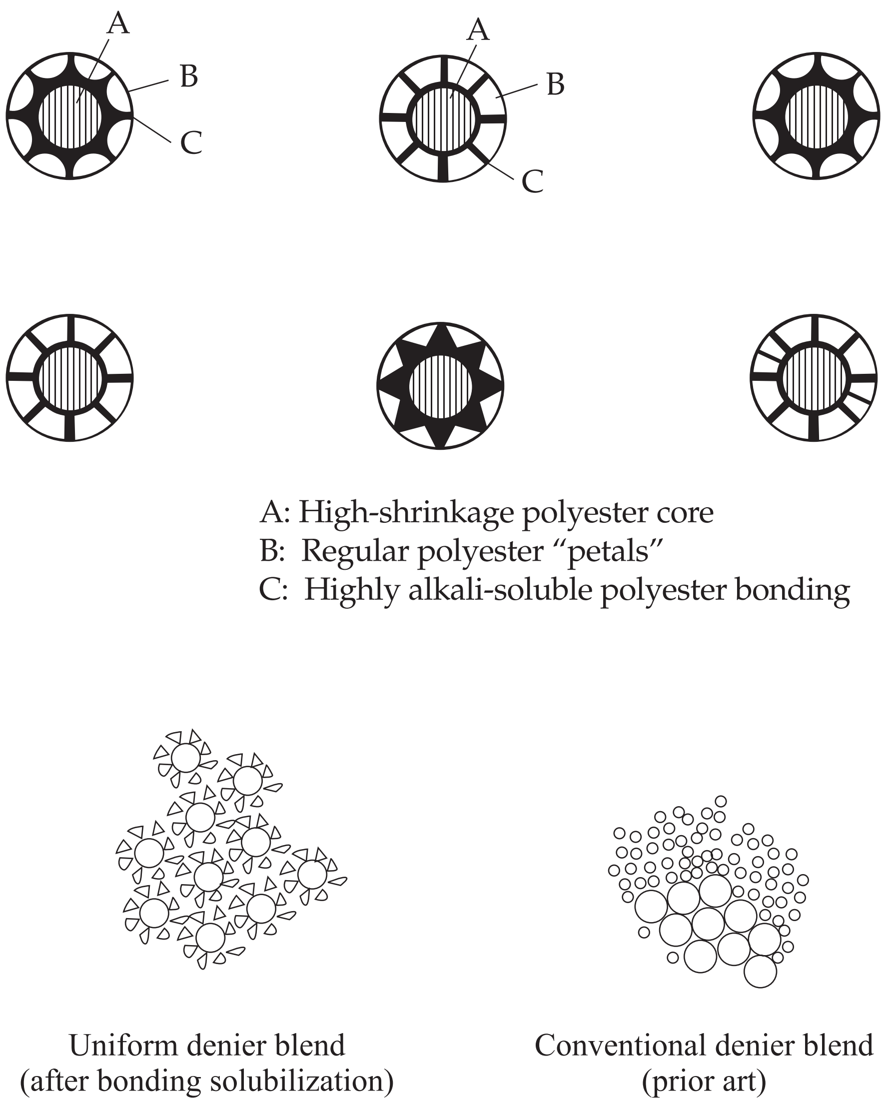
Source "Various Microfibers for Clothing." 1992. *JTN, The International Textile Magazine*. 450:81-83.

Figure 21. Radial sheath-core fibers (Kanebo, Ltd.)



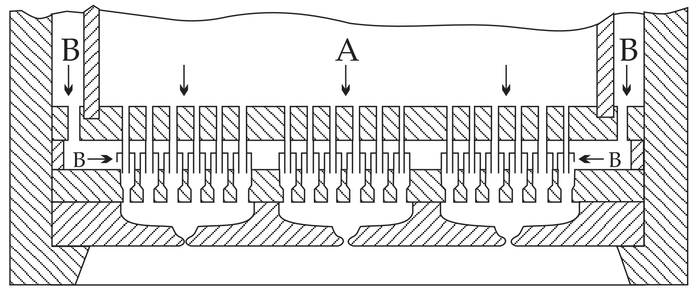
Source Hongu, T. and G.O. Phillips. 1990. *New Fibers.* West Sussex, England: Ellis Horwood Limited, a division of Simon & Schuster.

Figure 22. Ultrafine fiber wipers (Kanebo, Ltd.)

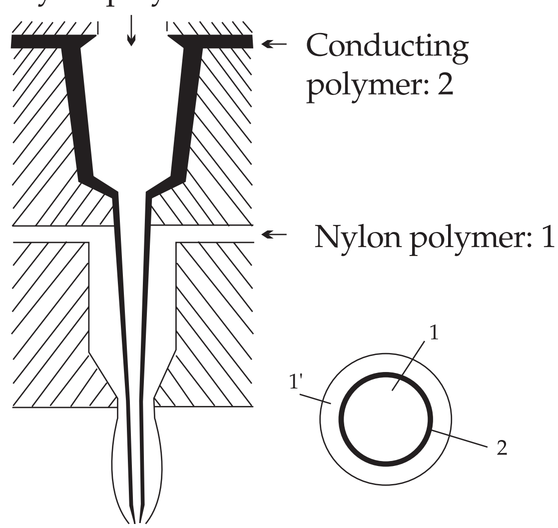


Source Kanebo, Ltd. 1990.

Figure 23. Cosmos-like fibers (Kanebo, Ltd.)



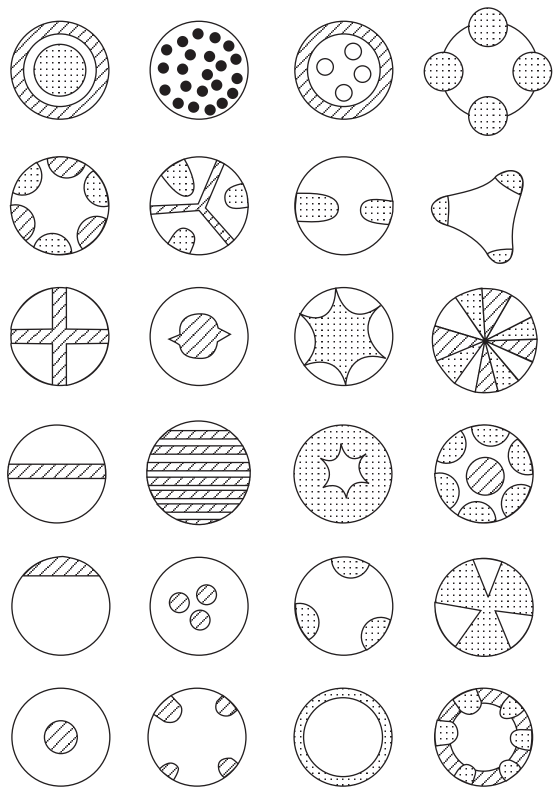
Two polymers



Three polymers

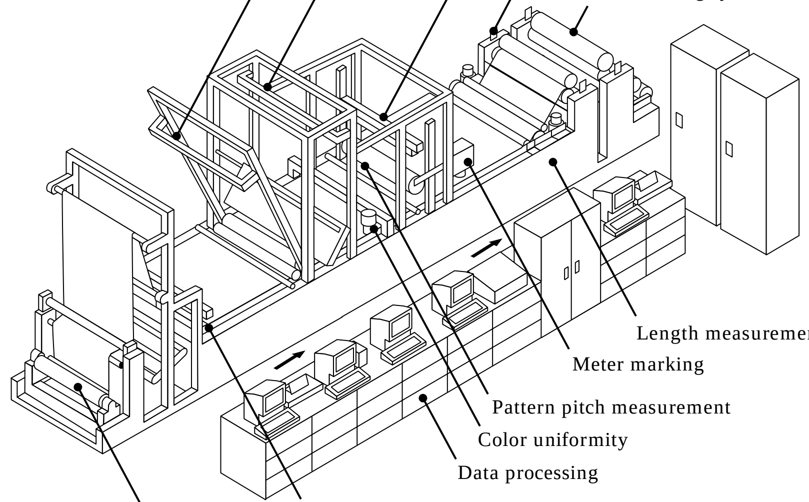
Source "Functional Fibers—Trends in Technology and Product Development in Japan." Toray Research Center, Inc.

Figure 24. Conjugate fibers—spinning heads

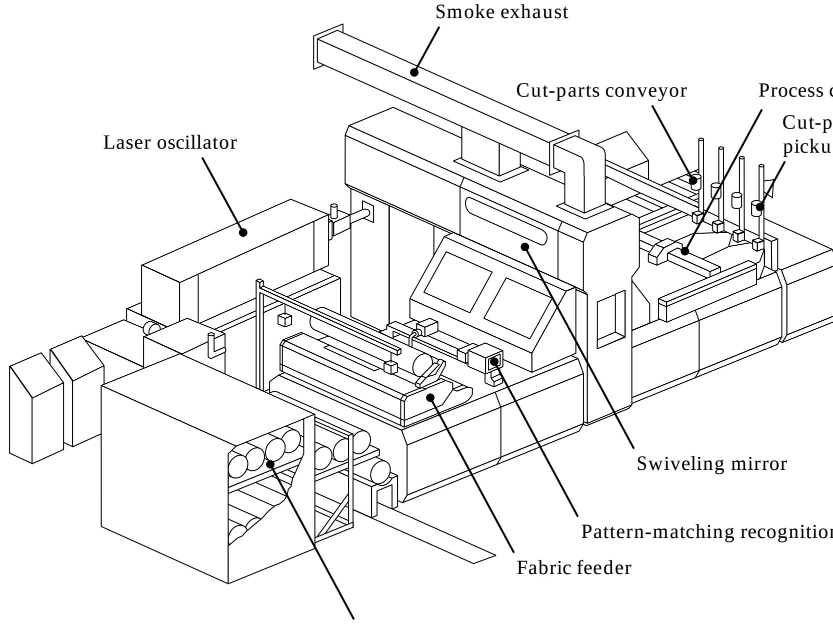


Source "Functional Fibers—Trends in Technology and Product Development in Japan." Toray Research Center, Inc.

Figure 25. Conjugate fibers—cross sections



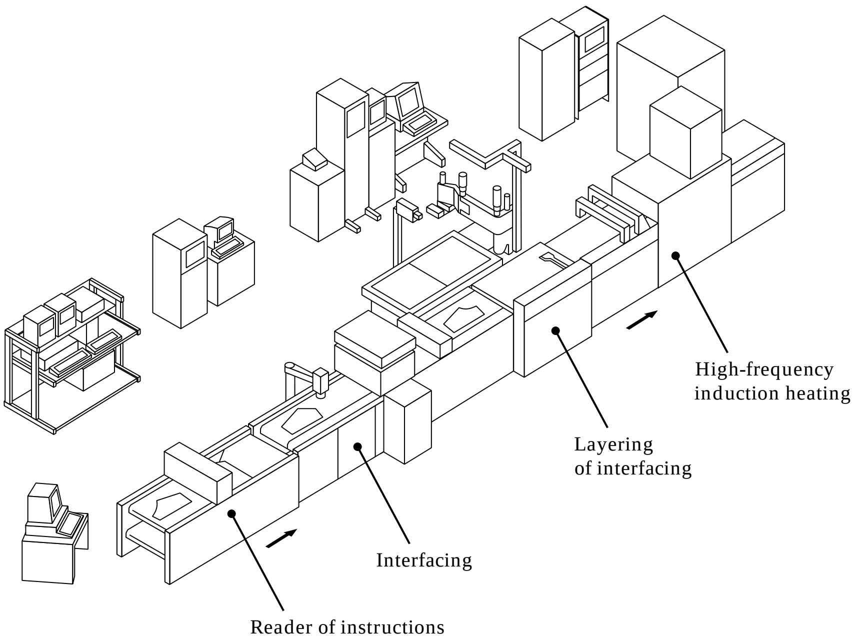
Intelligent Cloth Inspector



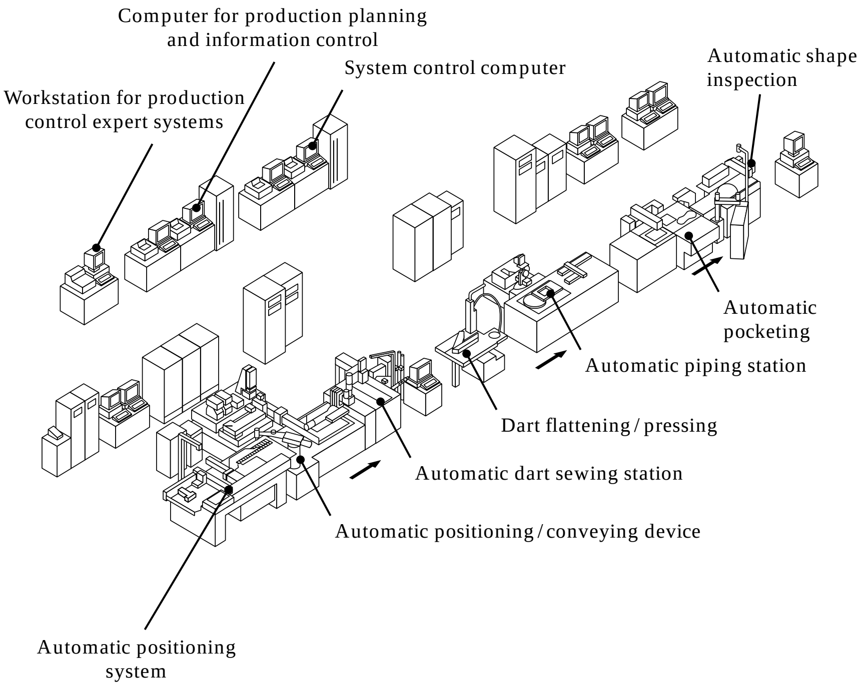
High-Speed Laser Cutter

Source "World Fashion Trade Fair." 1991. Technology Research Association of Automated Sewing System.

Figure 26. Automated apparel manufacture—I



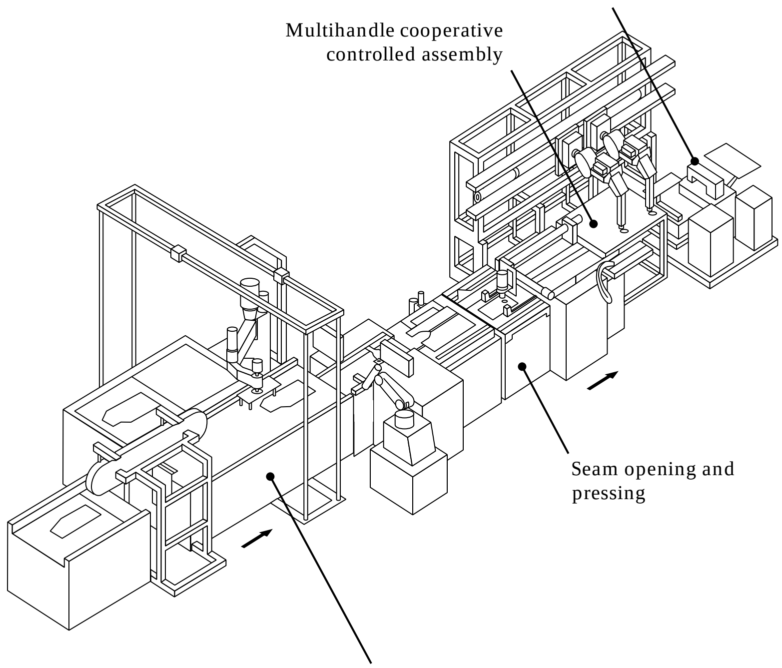
Preassembly System



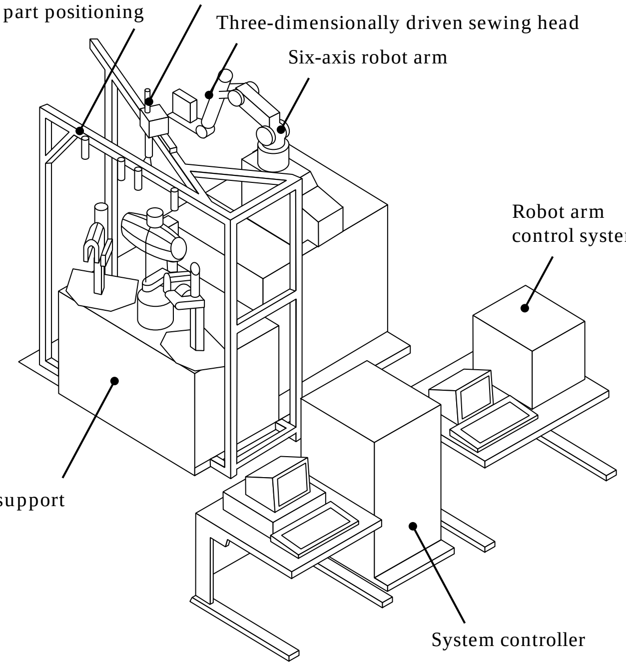
Multifunctional Sewing System

Source "World Fashion Trade Fair." 1991. Technology Research Association of Automated Sewing System.

Figure 27. Automated apparel manufacture—II



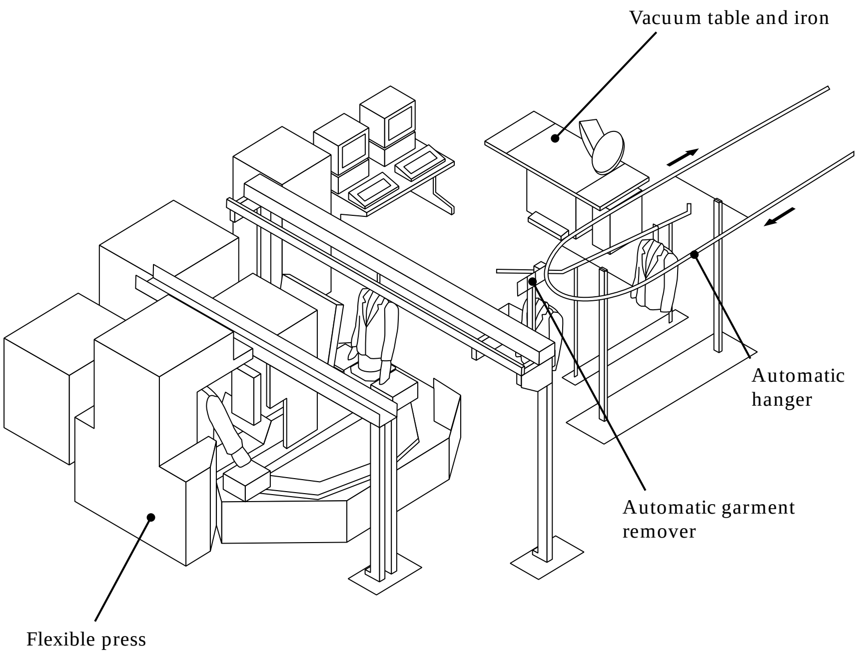
Joining/Sewing System



Three-Dimensional Seamer

Source "World Fashion Trade Fair." 1991. Technology Research Association of Automated Sewing System.

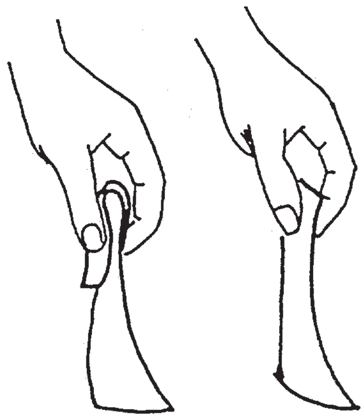
Figure 28. Automated apparel manufacture—III



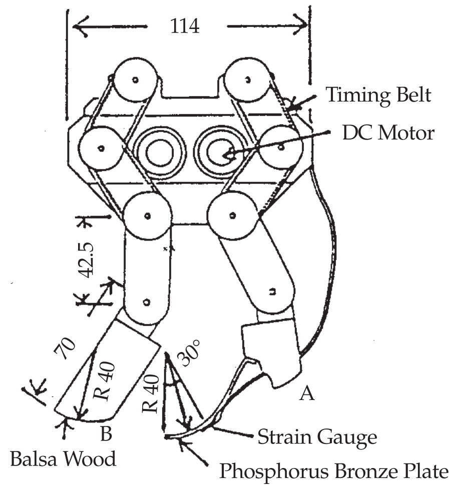
Three-Dimensional Flexible Press Subsystem

Source “World Fashion Trade Fair.” 1991. Technology Research Association of Automated Sewing System.

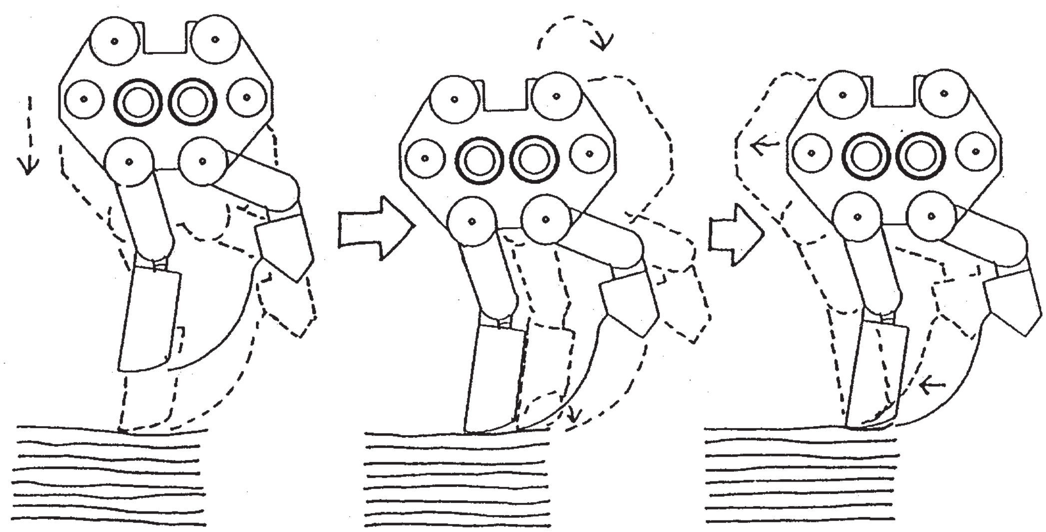
Figure 29. Automated apparel manufacture—IV



Two manual modes

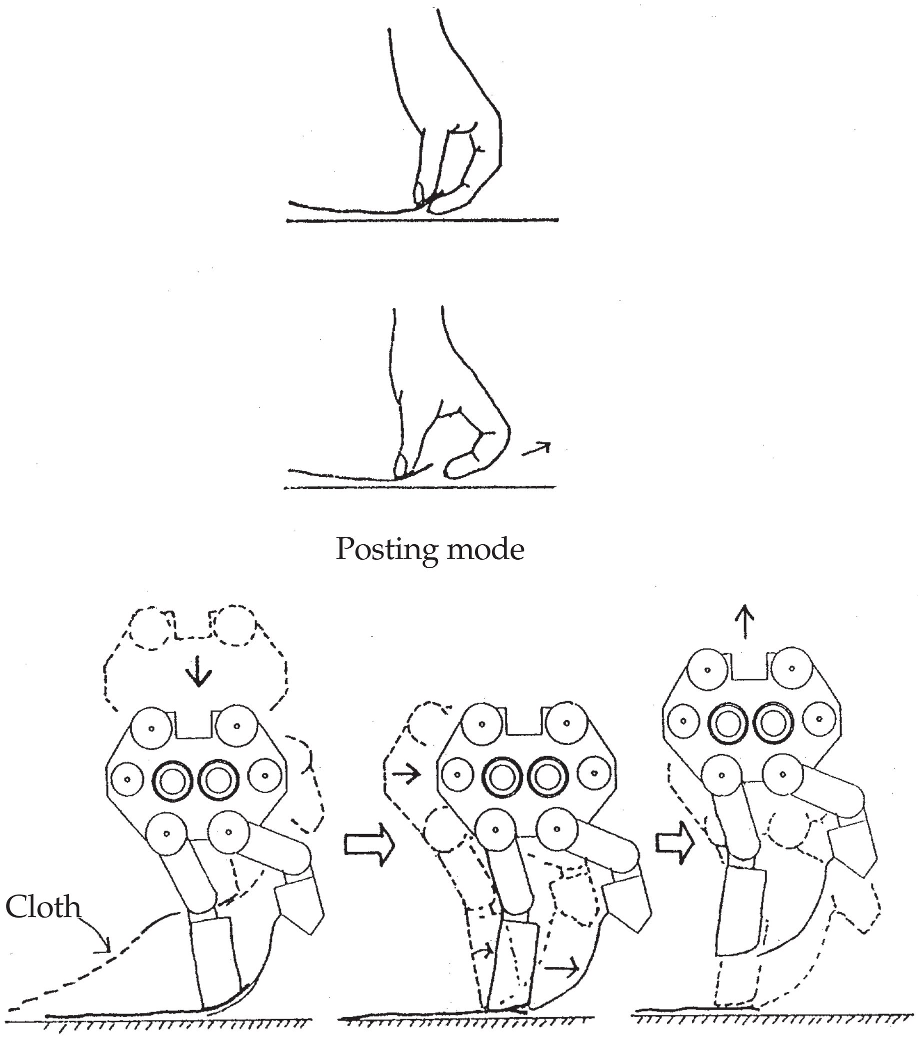


Robot hand



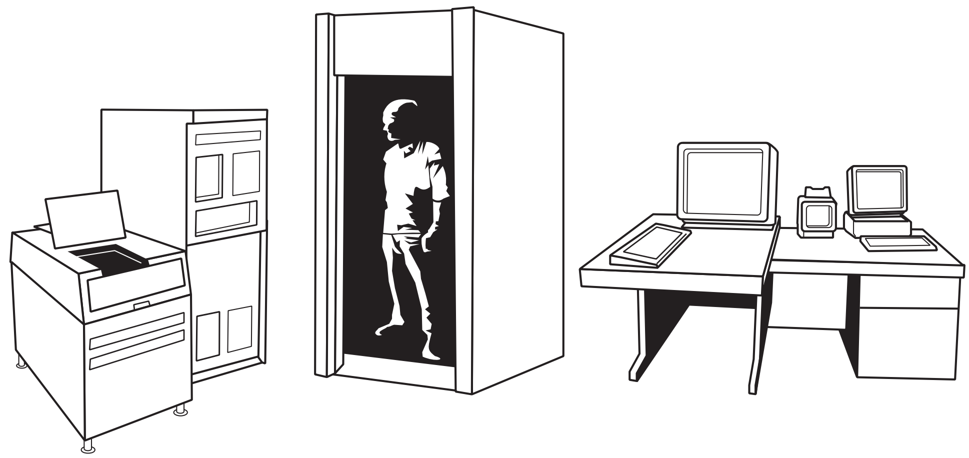
Source “Robot Hand with a Sensor of Cloth Handling.” 1991. *Bull. Res. Inst. Polym. Text.* 164.

Figure 30. Cloth picker—ply pickup

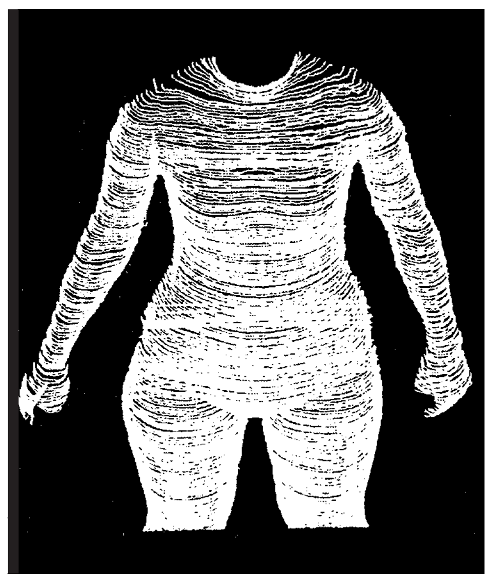


Source "Robot Hand with a Sensor of Cloth Handling." 1991. *Bull. Res. Inst. Polym. Text.* 164.

Figure 31. Cloth picker—ply laydown



Laser scanning booth



Three-dimensional body representation

Source Shibuya, A. and N. Aisaka. "Recent Technology of CAD System for Garment Design." 1992. *Bull. Res. Inst. Polym. Text.* 169(3):147-151.

Figure 32. Automated body measurement